Ocean-atmosphere interactions related to precipitation predictability and bias

A conversation starter following the detailed chapters in NOAA PPGC plan:

- Ch. 3 model biases
- Ch. 5 observation

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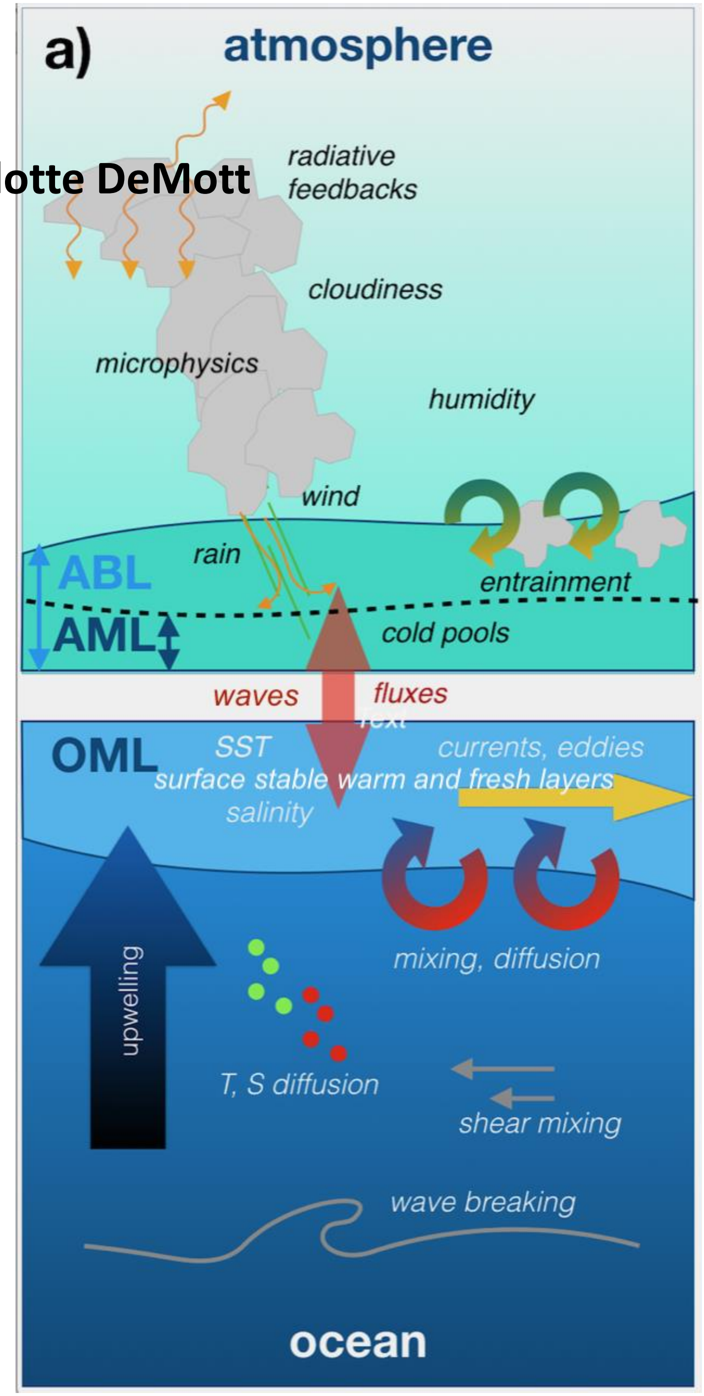
with grateful acknowledgement to collaborators and colleagues

Chris Fairall, Kyla Drushka, Jim Thomson, Andy Jessup, Bill Asher, Simon de Szoeke, Jim Moum, Byron Blomquist, Jian-Wen Bao, Prashant Sardeshmukh, Matthew Newman, John Albers, Michael Alexander, Antonietta Capotondi, Charlotte DeMott, Brandon Wolding, Juliana Dias, Maria Ghene, Ben Green, Shan Sun, Jim Edson, Carol Anne Clayson, Meghan Cronin, Lisan Yu, Shuyi Chen, Chidong Zhang, Scott Powell, Dongxiao Zhang, Jeff Reid, Aneesh Subramanian, Eric Maloney, David Randall, Ray Schmitt, Laifang Li, Sandy Lucas, NASA PBL Incubation Study, NASA Ocean Salinity Science Team/ Physical Oceanography / Precipitation Measurement Mission Team, US CLIVAR Workshop on atmospheric convection and air-sea interaction over tropical oceans

Outline

<u>Goal: Promote Discussion</u>
- What is holding us back?
- What are the key science questions?
- How can teams work together to solve the problem in new ways?
- What's going on, and what are experts doing about it right now?

c/o Charlotte DeMott

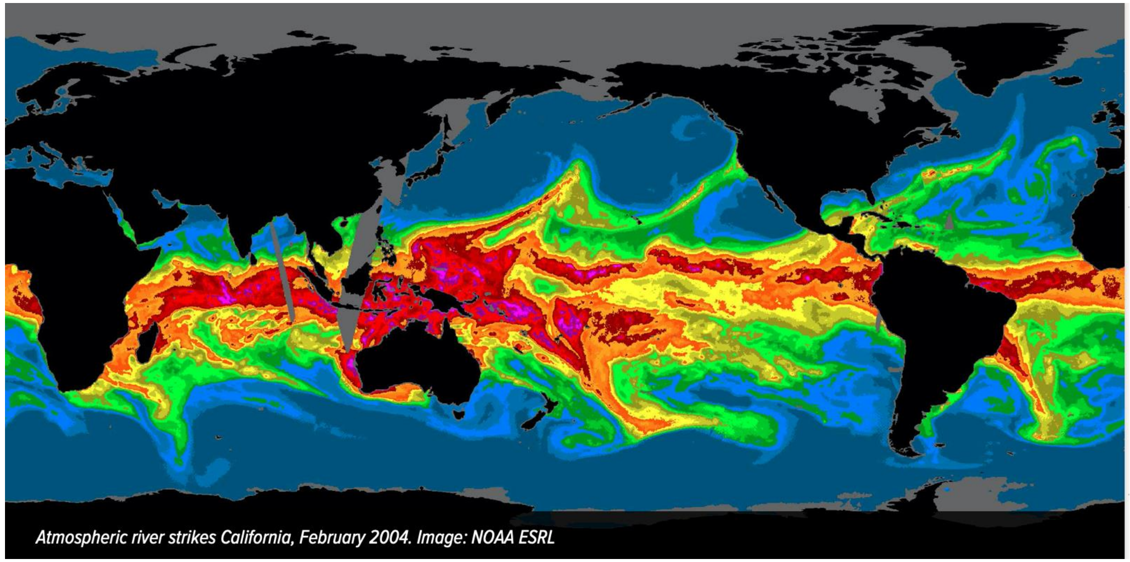


- Identify opportunities for model and observation teams to work together to:
  - harness sources of precipitation predictability over the ocean
  - reduce precipitation bias: over the ocean, through teleconnections, in moisture transport to CONUS

- … in the arena of **ocean-atmosphere exchanges**… away from home and close to home
  - SST
  - air-sea fluxes
  - marine atmospheric boundary
  - convection – surrounding environment
  - convective organization and upscale growth
  - teleconnections
  - on-shore flow

Ocean-atmospheric exchanges influence CONUS precipitation by altering:

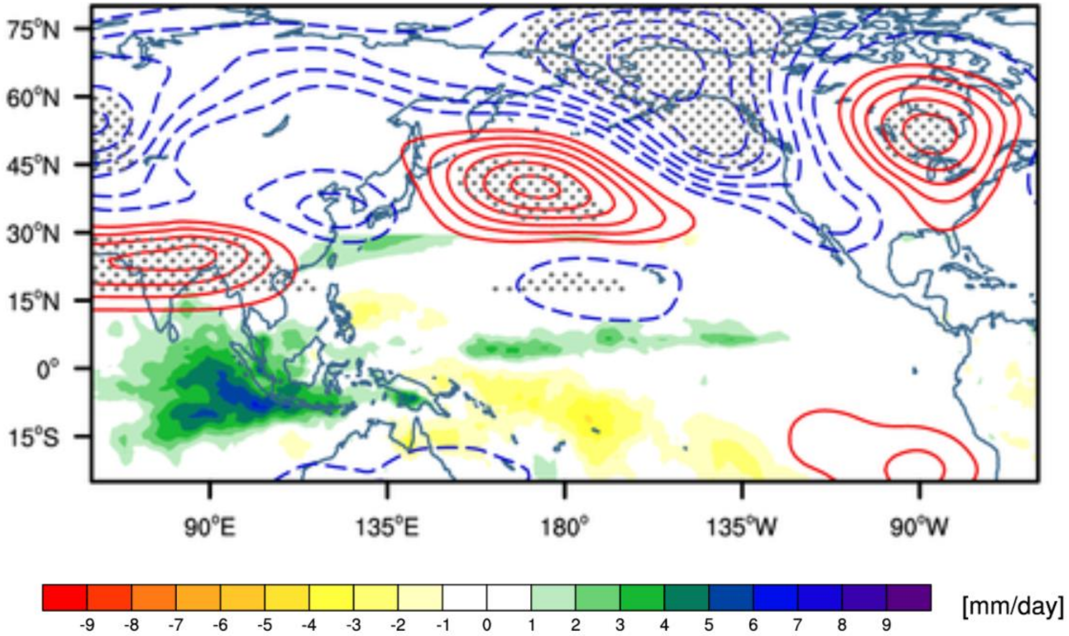
1. moisture transport; moisture sources and sinks



Total Precipitable Water, TPW

2. general circulation:
- **a) tropical convection**
- **b) teleconnection to CONUS**

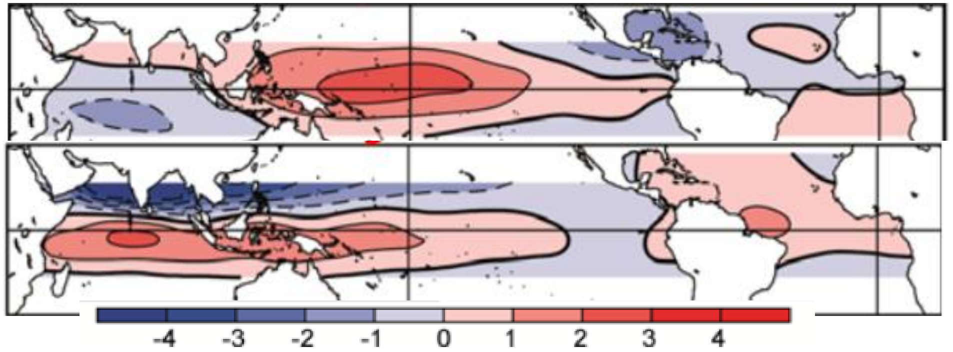
2 ways predictions can fail



Hendersen et al. 2017 - MJO Phase 3, GPCP precip and 250 mb height anomalies ERA-I

Major opportunities for ocean influence on CONUS precip

Tropical oceans: far Western Pacific and Maritime Continent

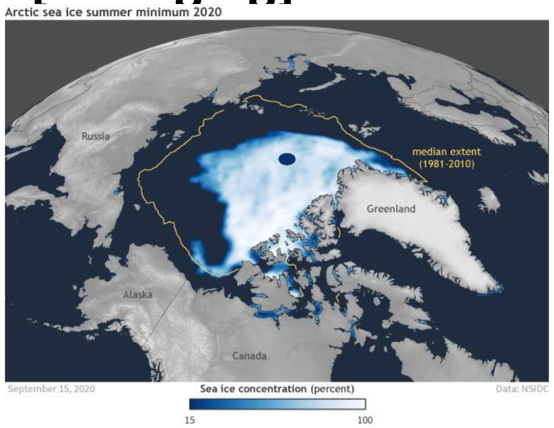


2 leading modes for sensitivity of CONUS precip/drought to SST

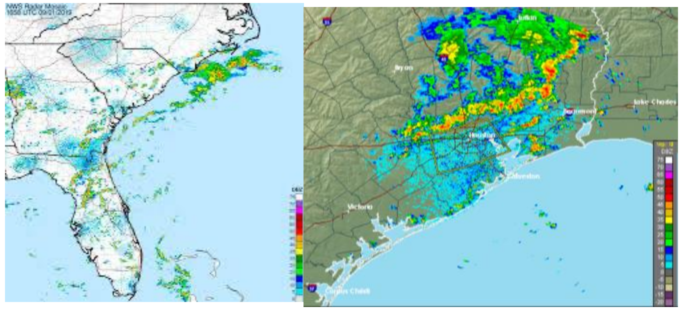
Sardeshmukh, Barsugli, Shin, 2021

Shin et al. 2006

[Emerging] Arctic



On-shore coastal flow



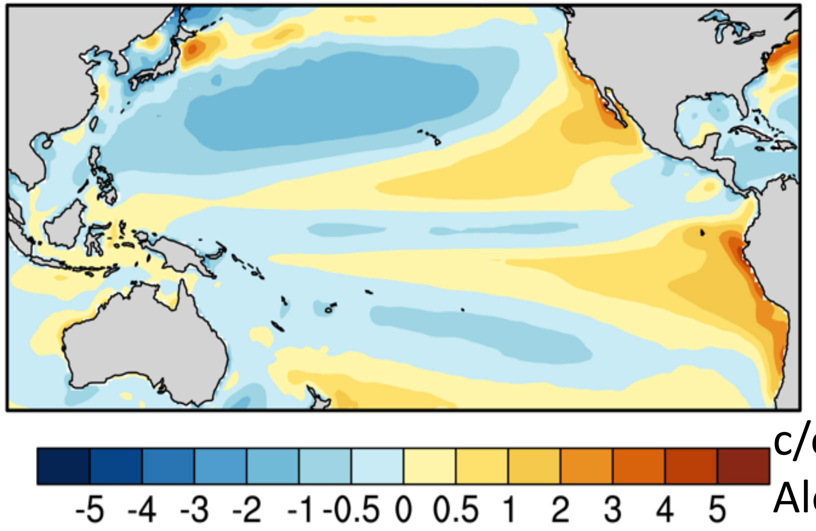
warm season US precip is analogous to Maritime Continent convection; lessons learned here will be holistically relevant

It is beneficial to target new innovations and investments in modeling and observations **in these regions… such as these current/new field campaigns:**

YMC, MINTIE, TPOS/OASIS, PISTON NASA Salinity, MOSAIC, long term obs TRACER, ATOMIC, CLEAR

The tropical mean state (ENSO) is not well predicted

CMIP6 SST bias

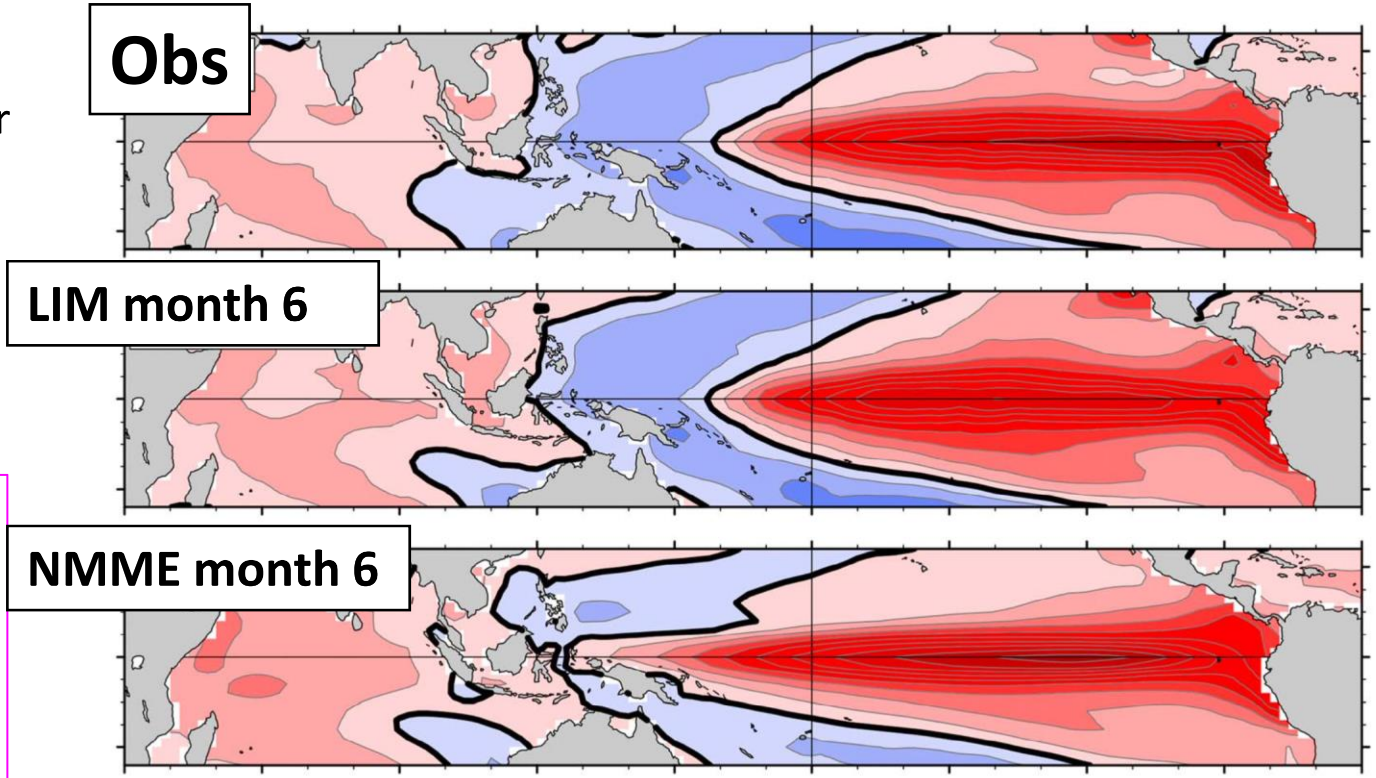


result:
30-60 W m^{-2} net flux error

c/o M. Alexander

Leading EOF of monthly SST

Newman and Sardeshmukh 2017



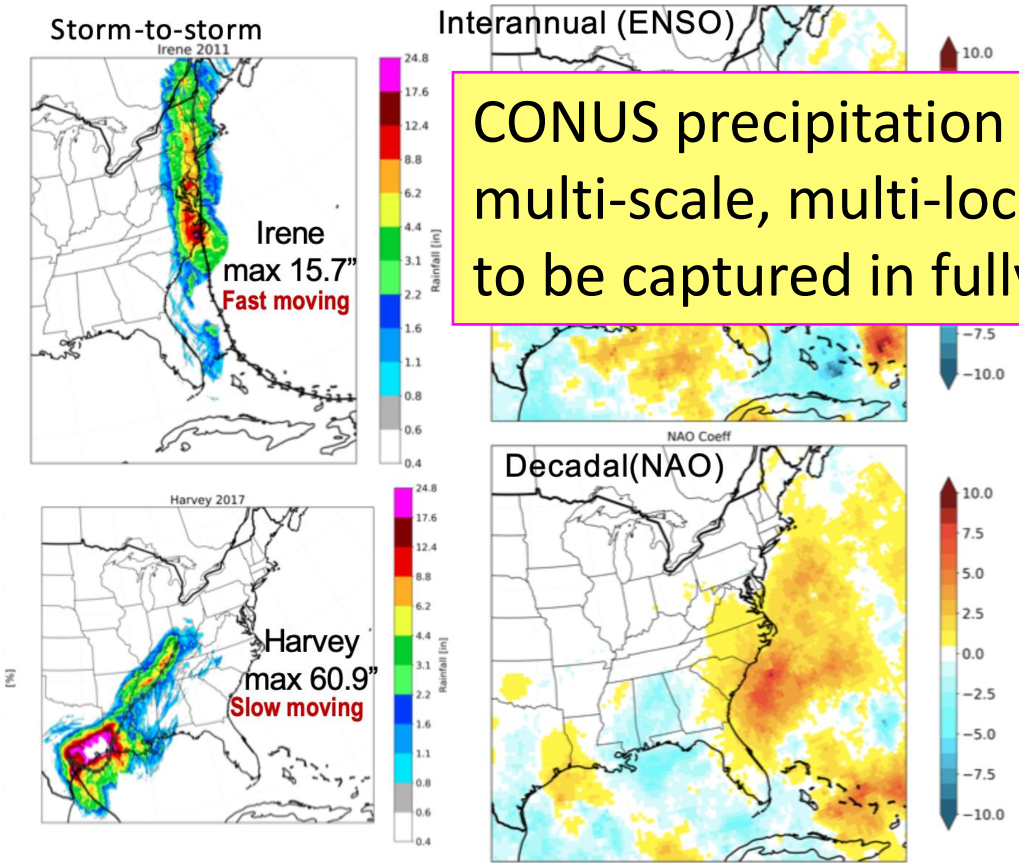
Unsurprisingly, bias also exists in fluxes and lower trop. moisture *(Kim 2017; Toh et al. 2017)*

Science Q: Why are the models doing this? How do precipitation and teleconnections respond?

Opportunity: Empirical models like LIM, model-analogs, and similar post-processing techniques can help overcome these errors and improve model skill

Closer to home… ENSO and NAO mean state affect land-falling hurricanes, atmospheric rivers, drought, Caribbean SST+winds, tornadoes, drought

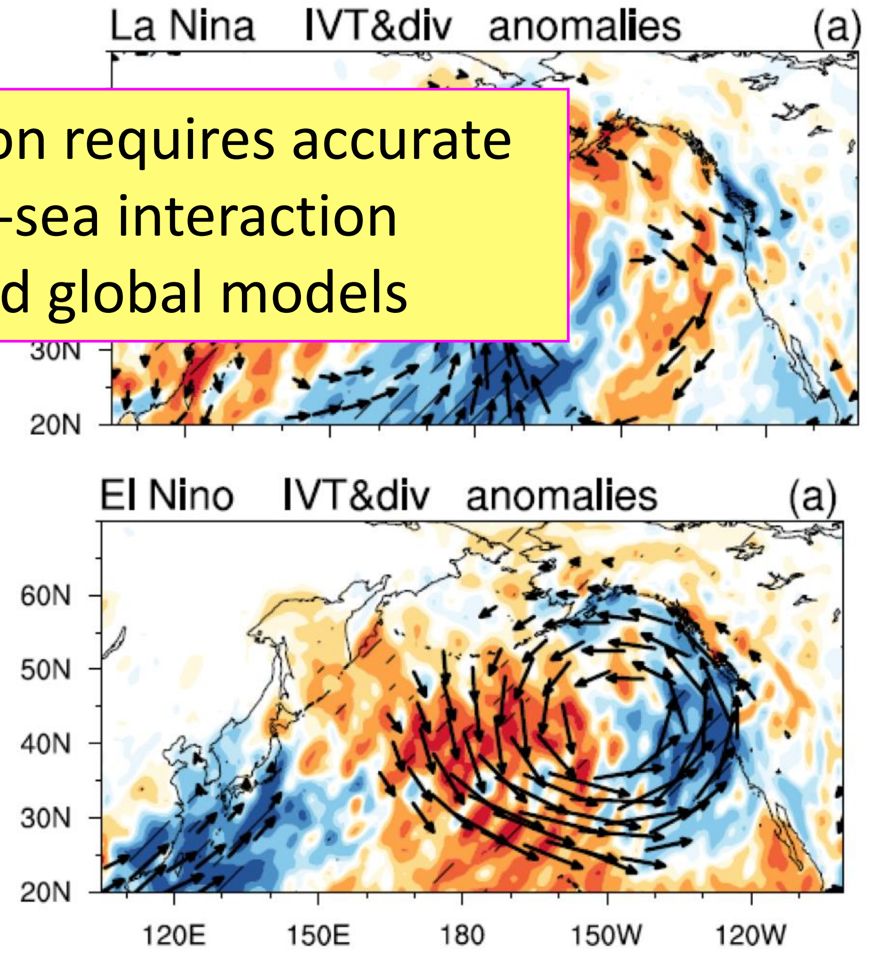
<u>Tropical Cyclone Rainfall …. EOFs</u>



Shuyi S Chen, Edoardo Mazza, University of Washington

(Xiong and Ren 2021)

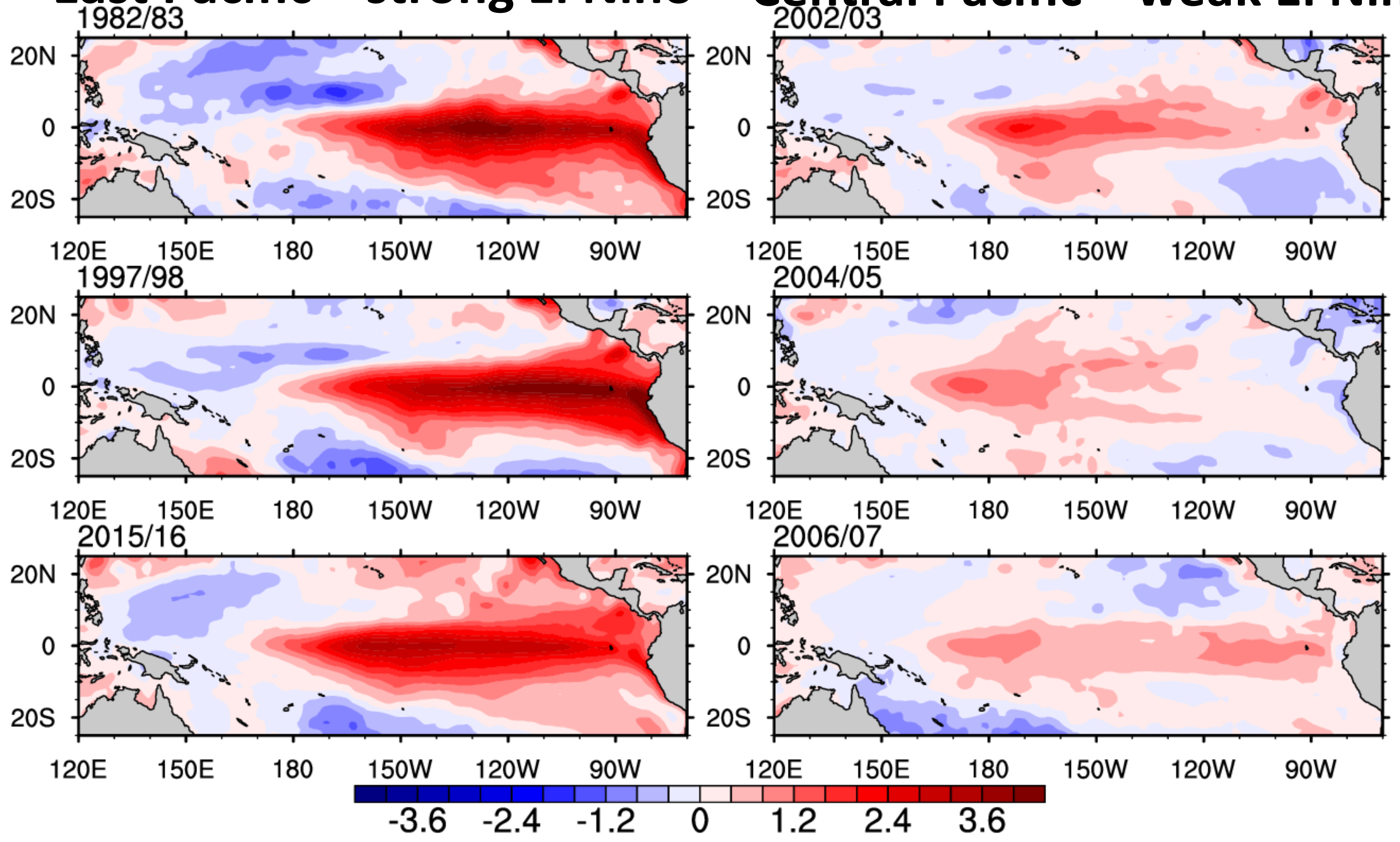
<u>integrated vapor transport and its divergence</u>



CONUS precipitation prediction requires accurate multi-scale, multi-location air-sea interaction to be captured in fully-coupled global models

The flavors of the tropical mean state (ENSO) are not well predicted

East Pacific ~ strong El Niño **Central Pacific ~ weak El Niño**



Science Q: Why are E- and C- type events preferred in some cases? How do they transition between types? What are the precursors? How does US precipitation respond?

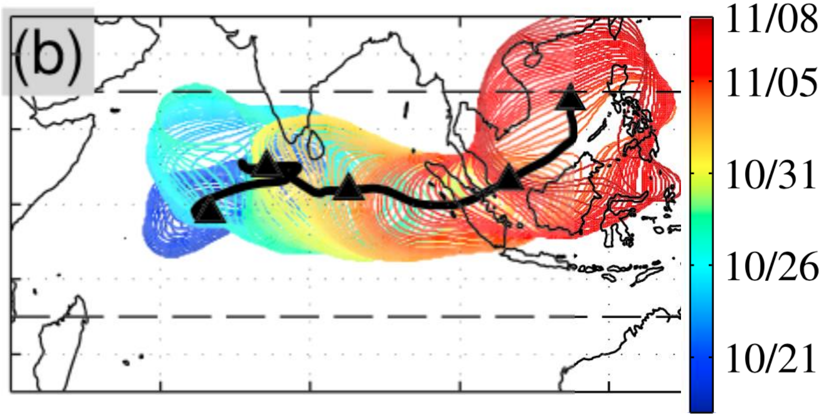
Opportunity: Fully coupled models and more data are needed to conduct sensitivity experiments

Capotondi et al., 2020

The flavors of the tropical variability (MJO) are not well predicted

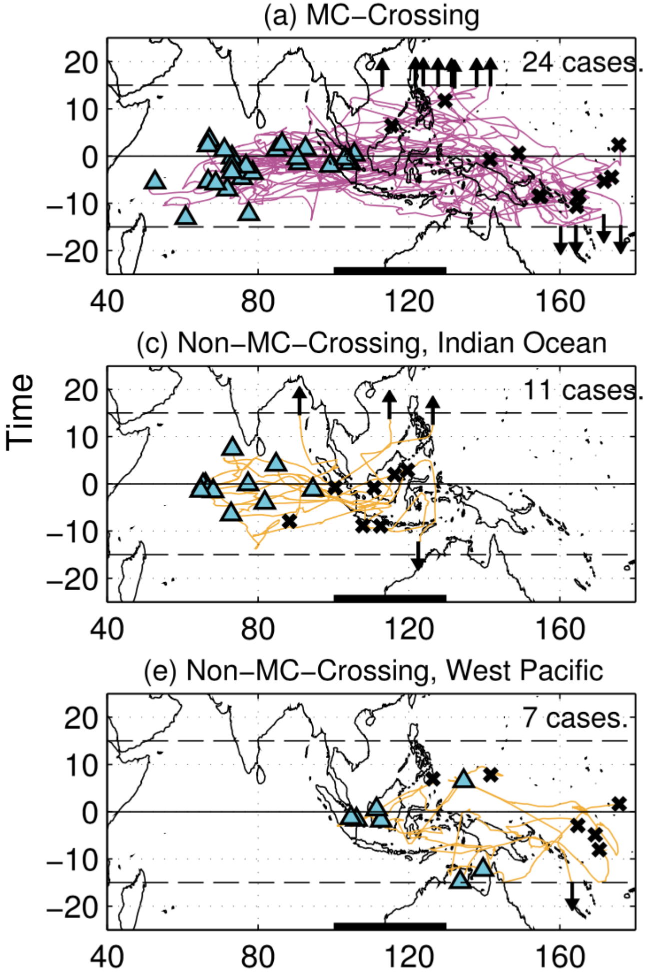
MJO convective envelope tracking

Kerns and Chen 2016

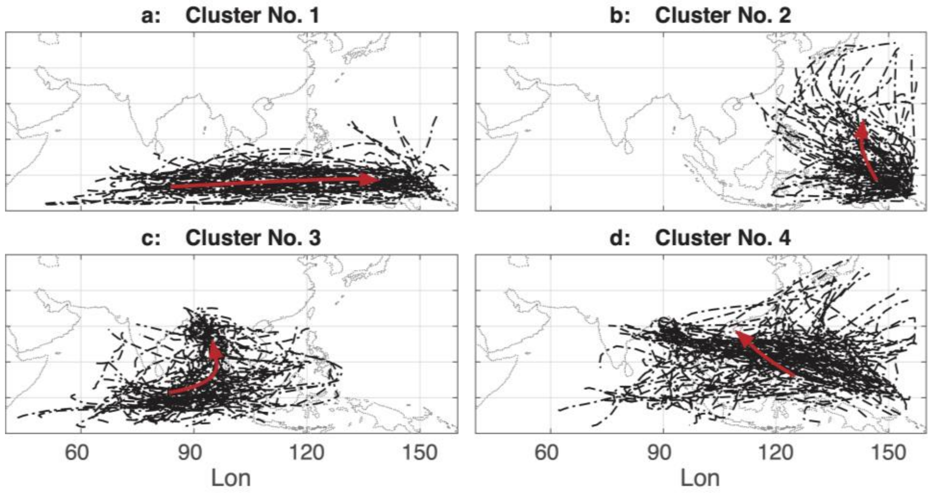


Boreal Winter MJO

Kerns and Chen 2016



Boreal Summer MJO, *Ma et al. 2021*



Science Q: Are the propagation mechanisms the same for different clusters? How do they teleconnect?

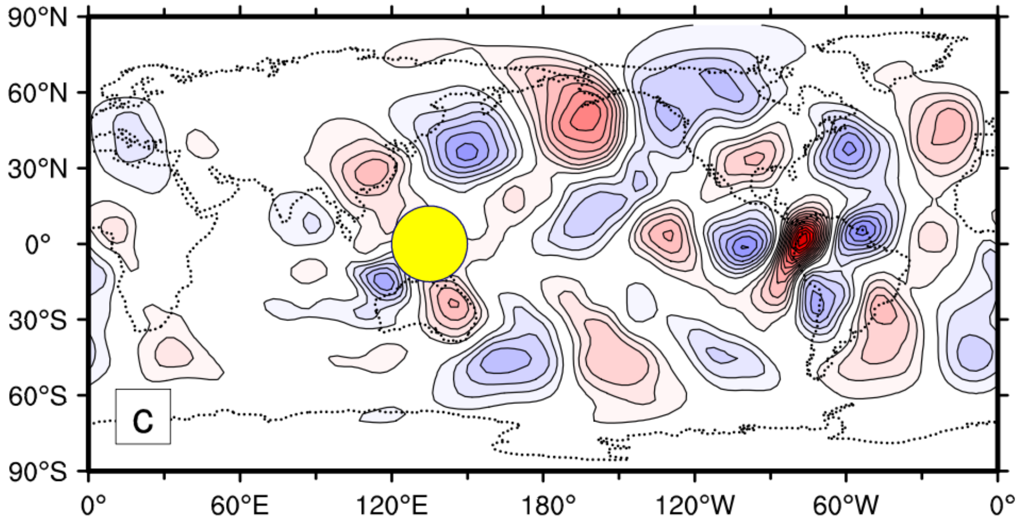
<u>Opportunity</u>: Compare model and obs with this time-evolving tracking framework... for MJO, AR, ENSO, etc.

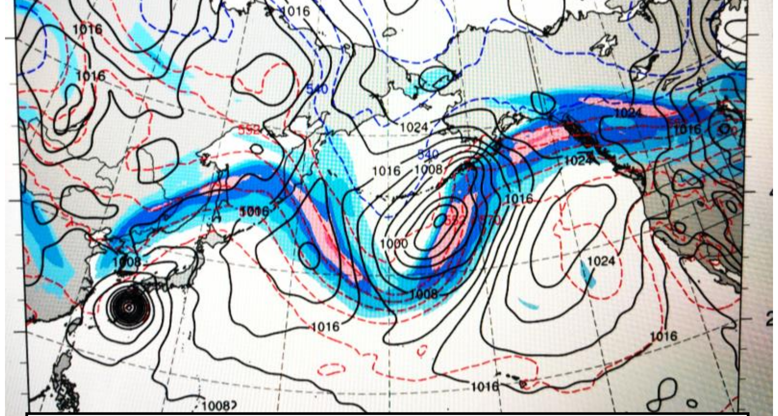
Synoptic scale weather events over ocean can also teleconnect and affect US precip

"extreme weather events in different parts of the world may be linked." - *Bosart et al. 2017, and many more*

2-day tropical heating pulses cause teleconnections to CONUS

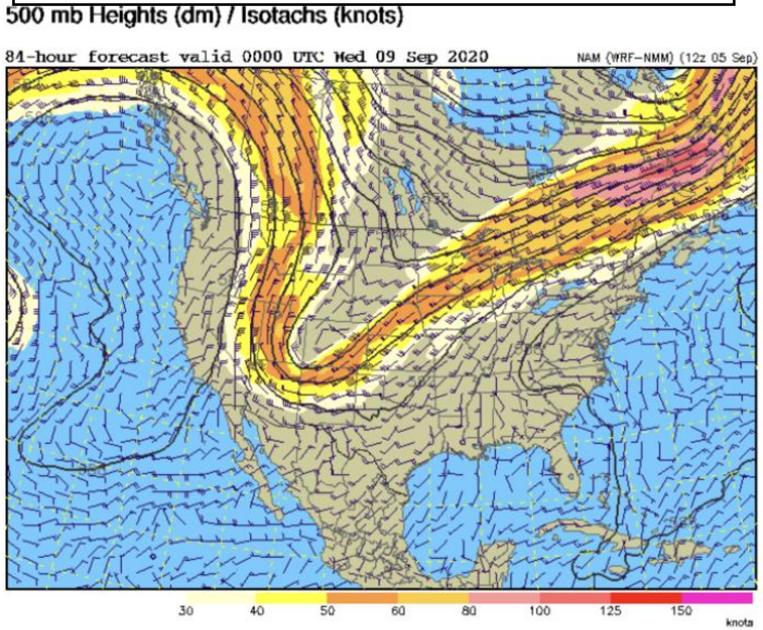
Branstator 2014: **Day 9** 300 mb wind response





High amplitude 250 mb jet stream and 500 mb trough downstream from Philippines typhoon…

8-9 Sept 2020: record smoke in CA and early snow in CO



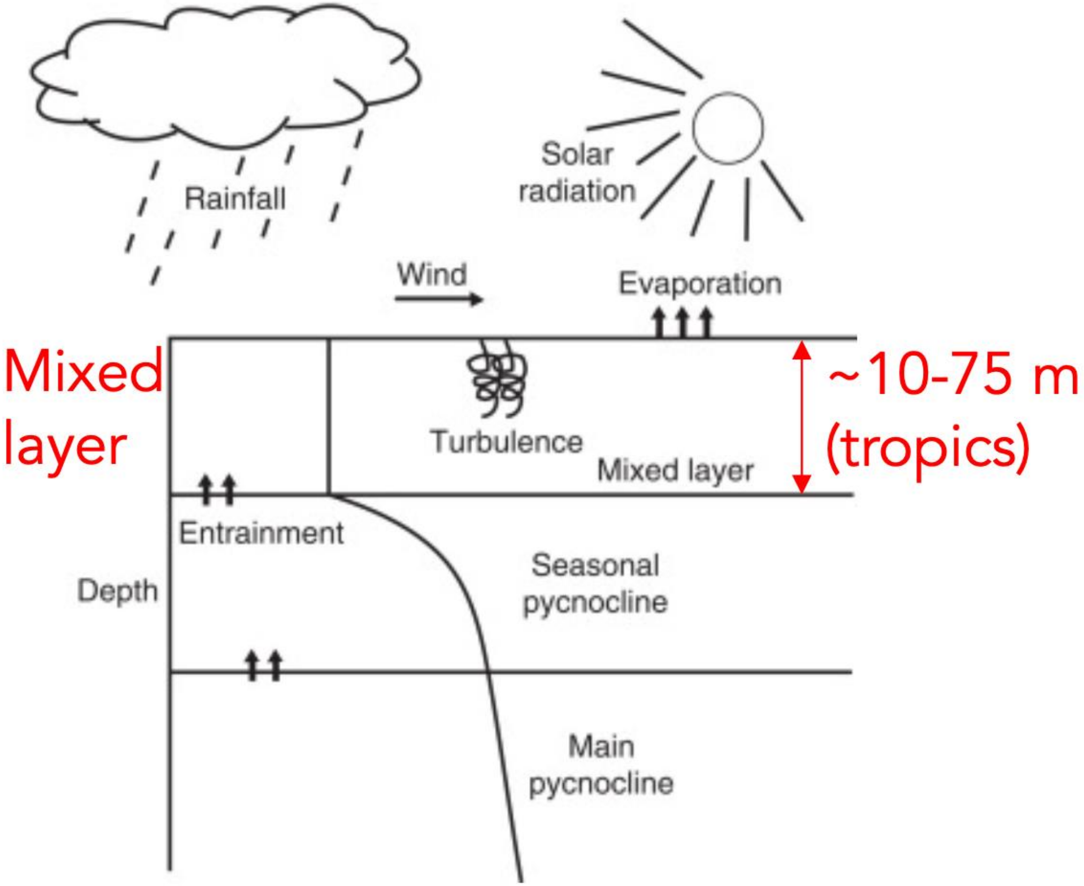
SST predictions are limited by limitations in modeling the ocean mixed layer

Opportunities:

- model **resolution** is improving, **coupled DA** advancements and experiments are ongoing
- DNS and field campaign data are revealing the **turbulent processes** in ocean needed to simulate SST, ocean heat content
- **turbulence** measurements have been added to surface and subsurface platforms: drifters, gliders, floats, and moorings
- new tropical ocean observing system will have better/more surface **fluxes**, higher ocean **vertical resolution**, and more sites
    - field campaigns bring more dense observations
- **UsX uncrewed ocean platforms** provide more data in harsh places (Arctic, waves, long-deployments)
- physical comparison and treatment of **fluxes** (COARE)

Challenges:

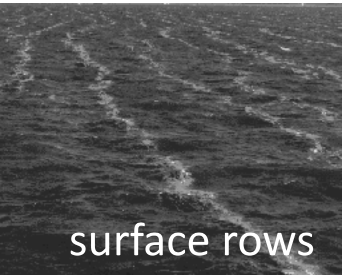
- **horizontal resolution + bottom topography** -> upwelling, mixing, mesoscale and submesoscale SST fronts, eddies, and filaments
- **turbulence** -> mixing, tides, waves (surface and interior)
- **vertical resolution** -> near-surface stable layers, barrier layers, upper ocean currents, ocean heat content, mixed layer depth
- **coupled DA** -> surface fluxes, waves, cloud shading



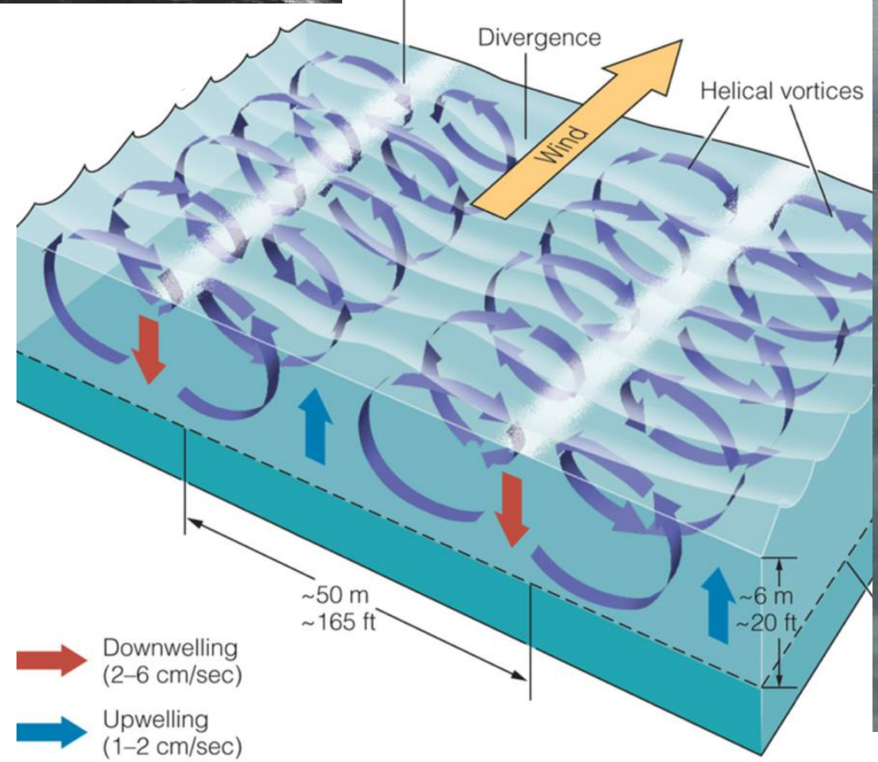
Sprintall and Cronin, 2001

Ocean models and reanalysis lack realistic mixing/turbulence => major limitation for modeling SST

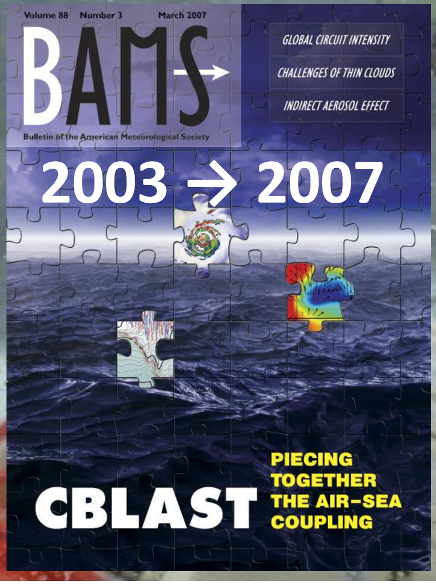
Moum 2021: Variations in ocean mixing from seconds to years



Langmuir Circulations



Waves, Sea Spray, High Winds, High Shear, Entrainment



DYNAMO MJO Westerly Wind Burst: 25% more SST cooling caused by **ocean shear and entrainment** across base of ocean mixed layer than by surface fluxes (*Moum et al. 2014, 2016)*

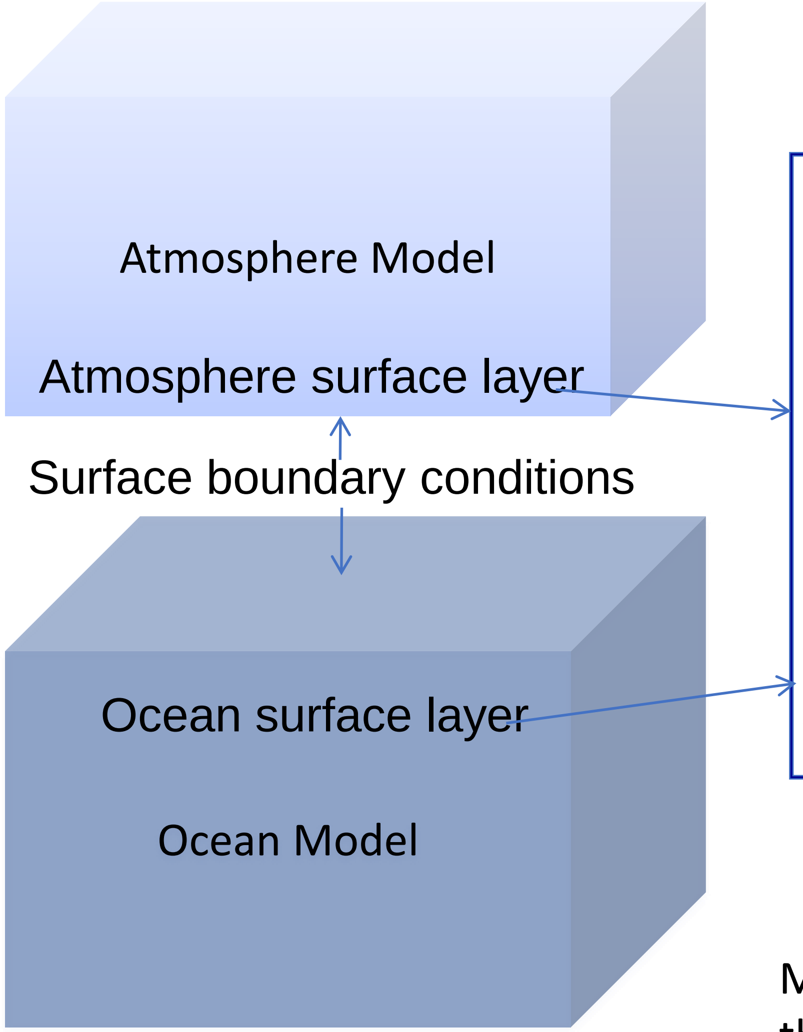
Opportunity:

- UsX: turbulence measurements can be made on drifters, profiling floats, moorings, towed ship profilers

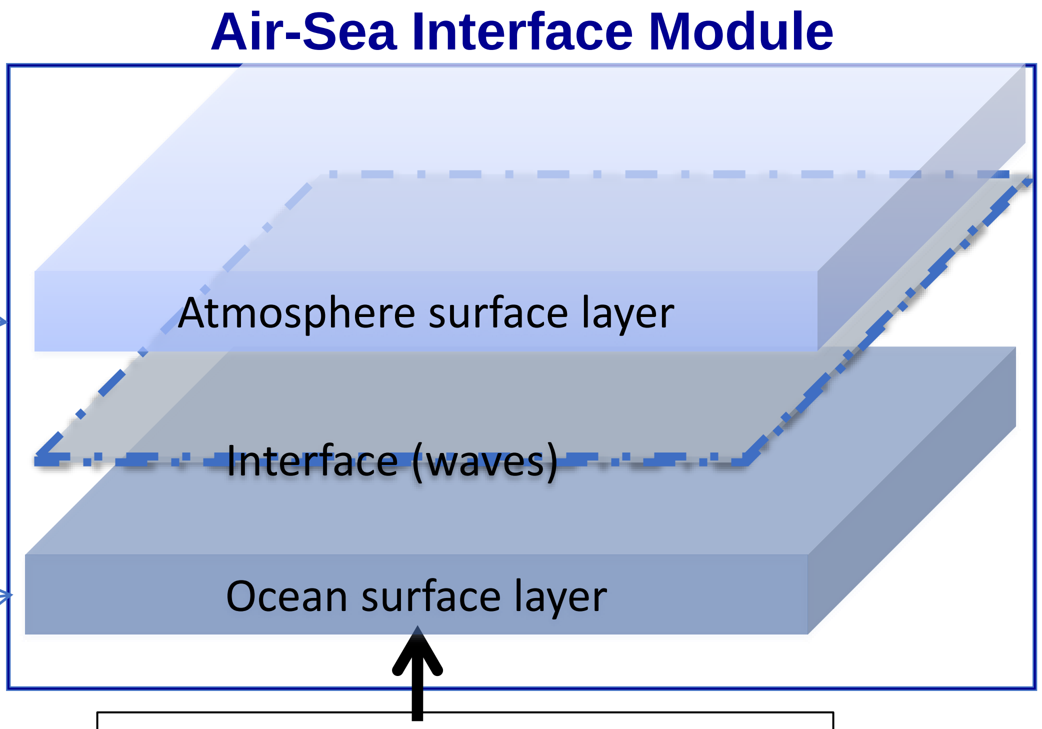
Science Q: What are the fluxes and SST during high winds, sea spray, big waves? (CBLAST: *Chen et al., Black et al. Edson et al. 2007)*

Coupled atmosphere-wave-ocean models are successful in research models, and are needed operationally

Shuyi Chen, Univ of Washington



Unified Wave INterface (UWIN)
for Coupled Models (CM)
Chen et al. (2013), Chen & Curcic (2016)

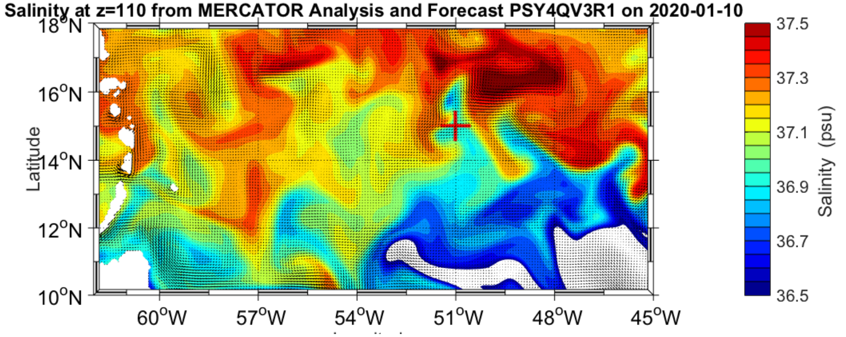


need coupled observations and coupled data assimilation

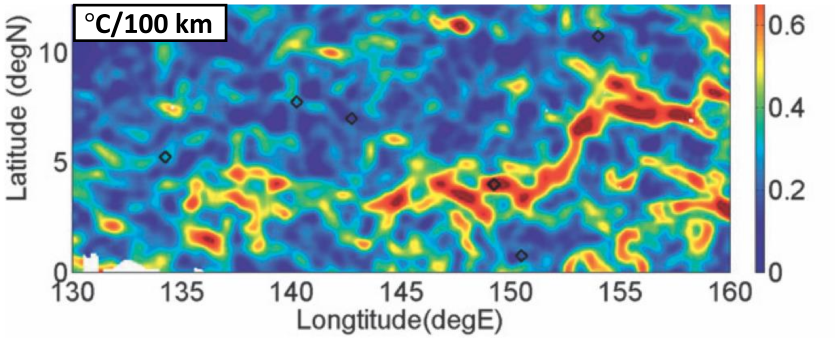
Model can use a consistent single set of coupled equations across the air-sea interface instead of separate drag coefficients

Increasing ocean horizontal resolution improves model skill in SST and precipitation

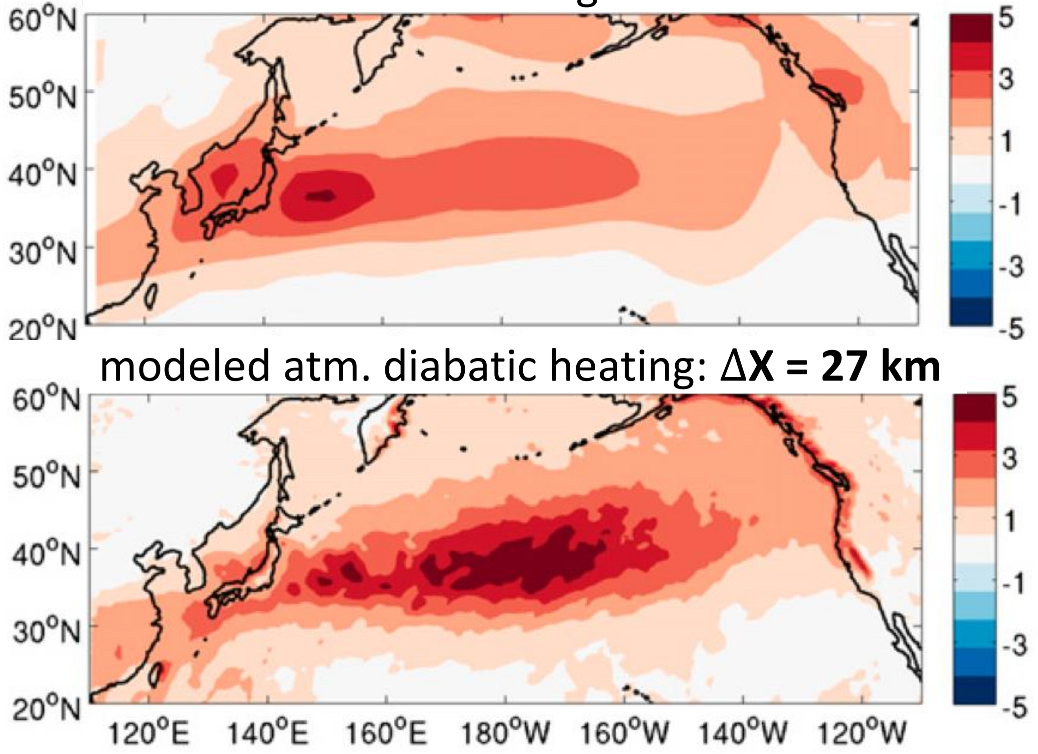
Ocean reanalysis is becoming finer (MERCATOR)



Laplacian of SST excites rainfall… sensitive to SST product chosen, *Li and Carbone 2012*



Ocean mesoscale eddies in warm western boundary currents have both local and remote influences on the atmospheric storm track:



Ma et al. 2017, Saravanan and Chang 2019

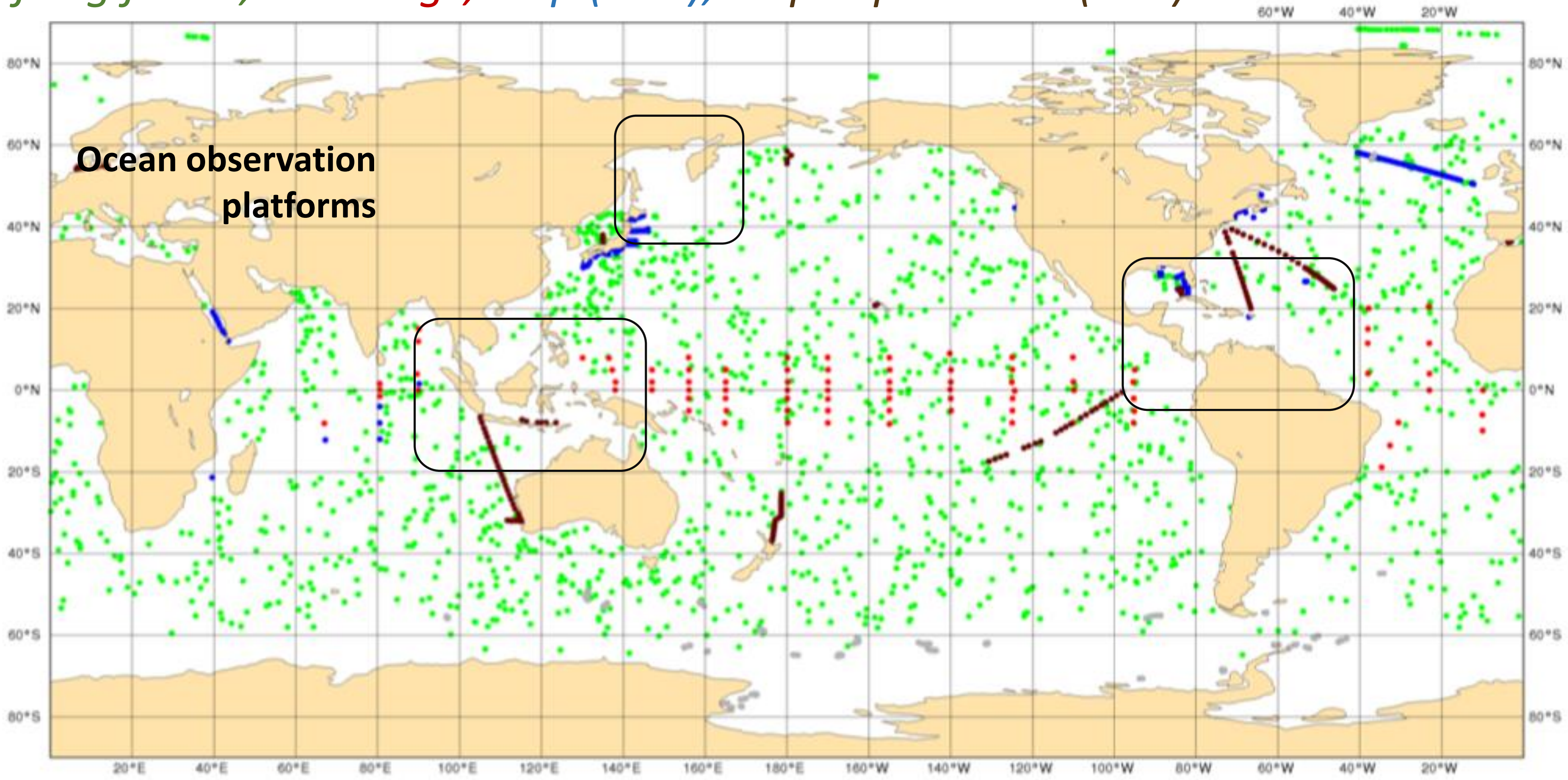
<u>SST gradients (Laplacians) enhance air-sea fluxes and precip, forced by ocean submesoscale and mesoscale fronts, eddies, filaments</u>

Lindzen and Nigam 1987, Soloviev and Lukas 1997, Woolnough et al. 2000, 2001, Costa et al. 2001, Chelton et al., 2004; Small et al., 2008, Back and Bretherton et al. 2009a,b, Li and Carbone 2012, Carbone and Li 2015, de Szoeke and Maloney 2020, Sullivan et al. 2020

In-situ observations of SST or ocean mixed layer depth to validate or initialize models are **sparse**

5 days of ocean observation platforms

Drifting floats, Moorings, Ship (CTD), Ship expendable (XBT)

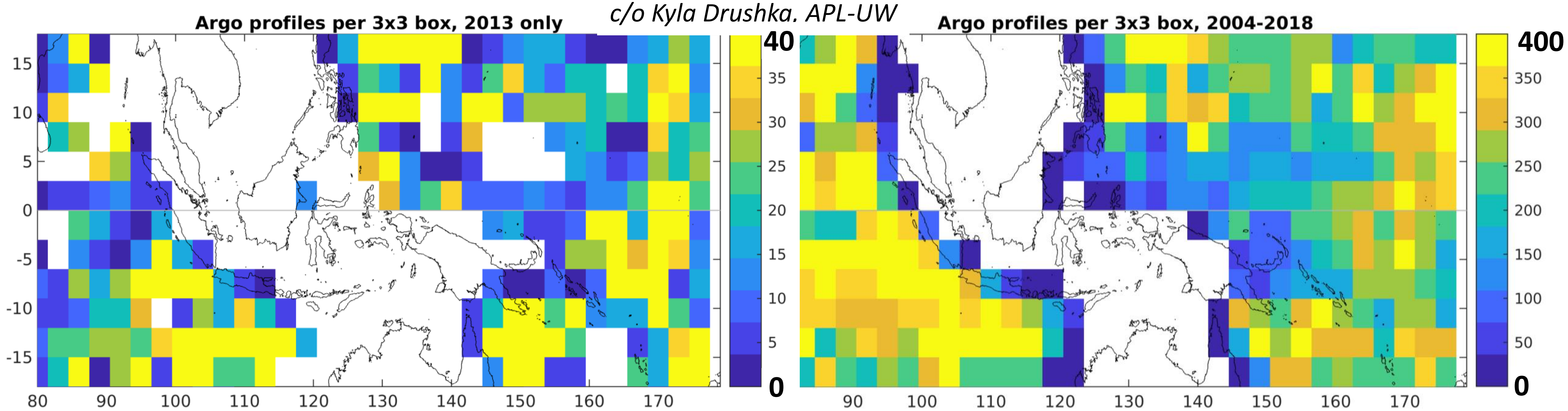


Argo floats profile T from 2 – 1000 m, every 9 days, approximately 1 per 1 month per 3° X 3 ° box

Within the Maritime Continent: ***no*** direct in-situ data of SST, ocean mixed layer depth, or air-sea fluxes are available to initialize or validate models

Argo floats and surface drifters cannot sample within Maritime Continent due to Exclusive Economic Zone (EEZ) restrictions.

c/o Kyla Drushka, APL-UW



In 2013, a highly sampled year, Argo sampled only 0-40 times per year per 3°x3° box

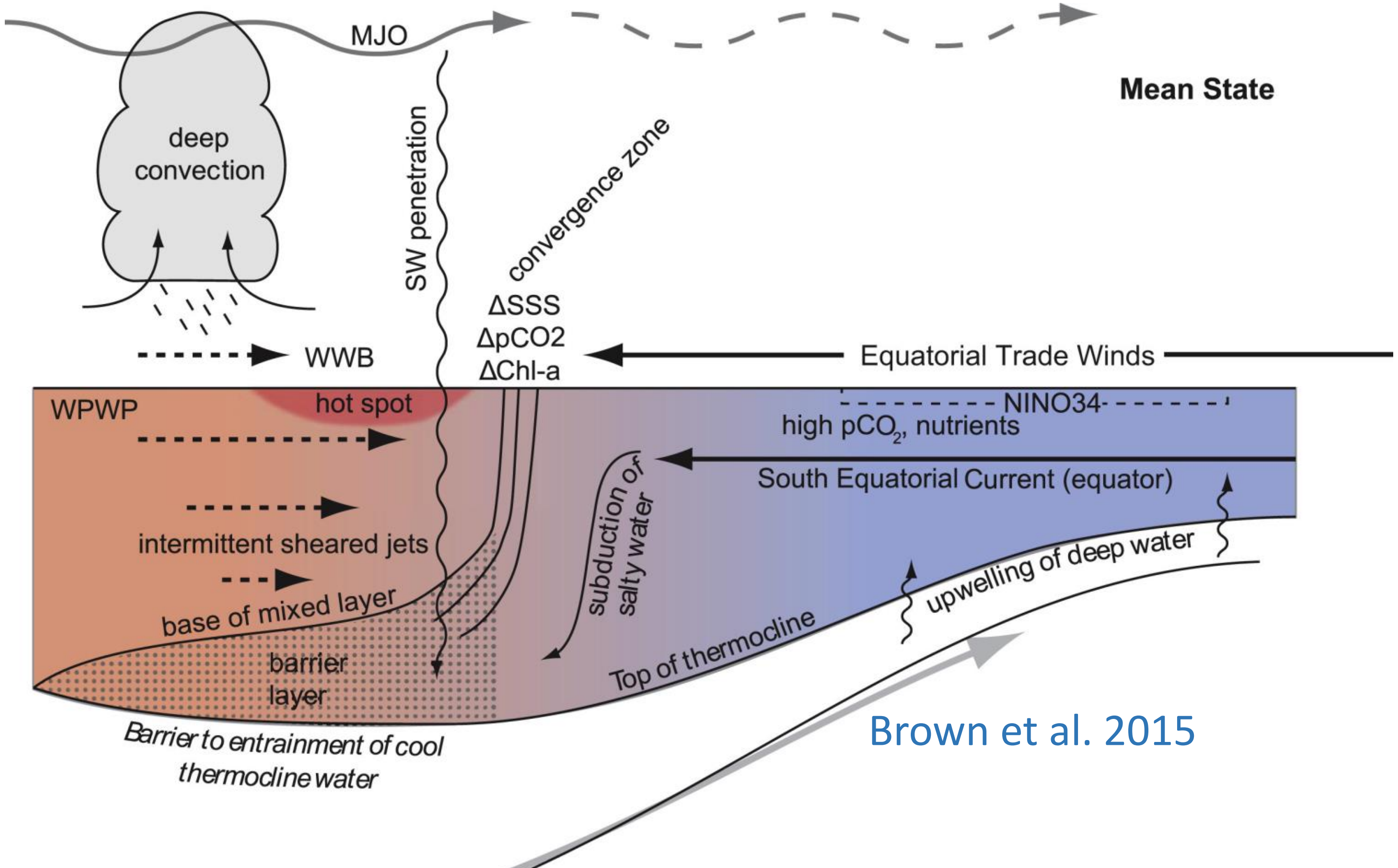
From 2004-2018 (14 years), 0-400 Argo samples have been collected per 3°x3° box across Oceania

Challenge: Even outside EEZ, Argo floats …
… cannot sample **seasonal or subseasonal** scales (≤ 30 samples/yr)
… cannot sample **regional variability** across basin
… cannot sample **above 2 m depth, or above 5 m** before 2018

Opportunity: attempt to obtain research permits for field campaigns. International capacity building is critical to partnerships; TPOS/OASIS new flux and ocean sites

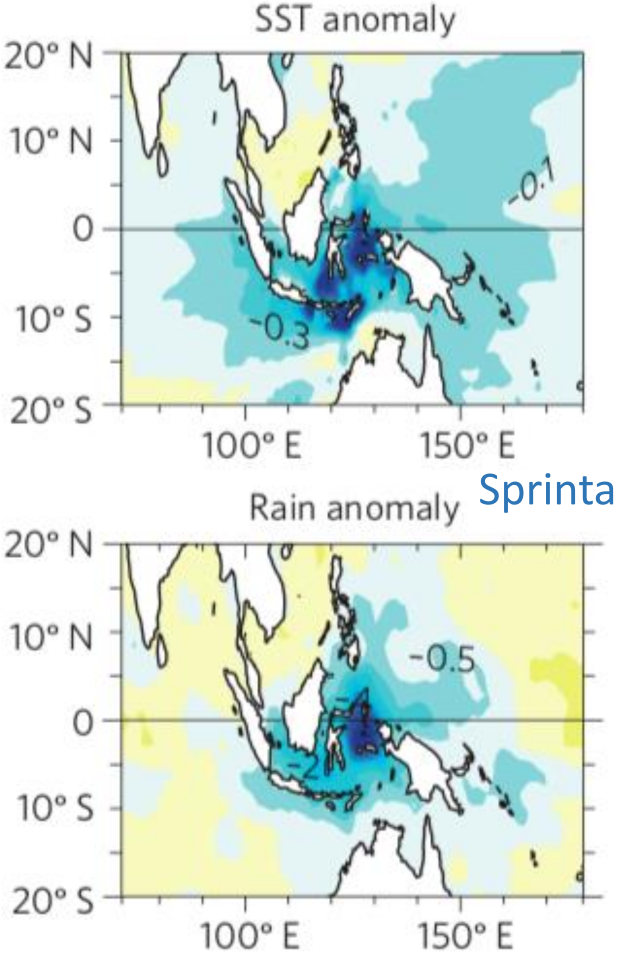
We must better understand, measure, and model 3-D subsurface ocean mixing, currents, tides, stability to better predict SST, ocean heat content, and precipitation

Pacific mean state: complex bottom topography, strong seasonally reversing current systems, air-sea-land interaction, barrier layers, and strong mixing by tides and internal waves.



Brown et al. 2015

Modeled anomalies caused by neglecting tidal mixing



Sprintall et al. 2014

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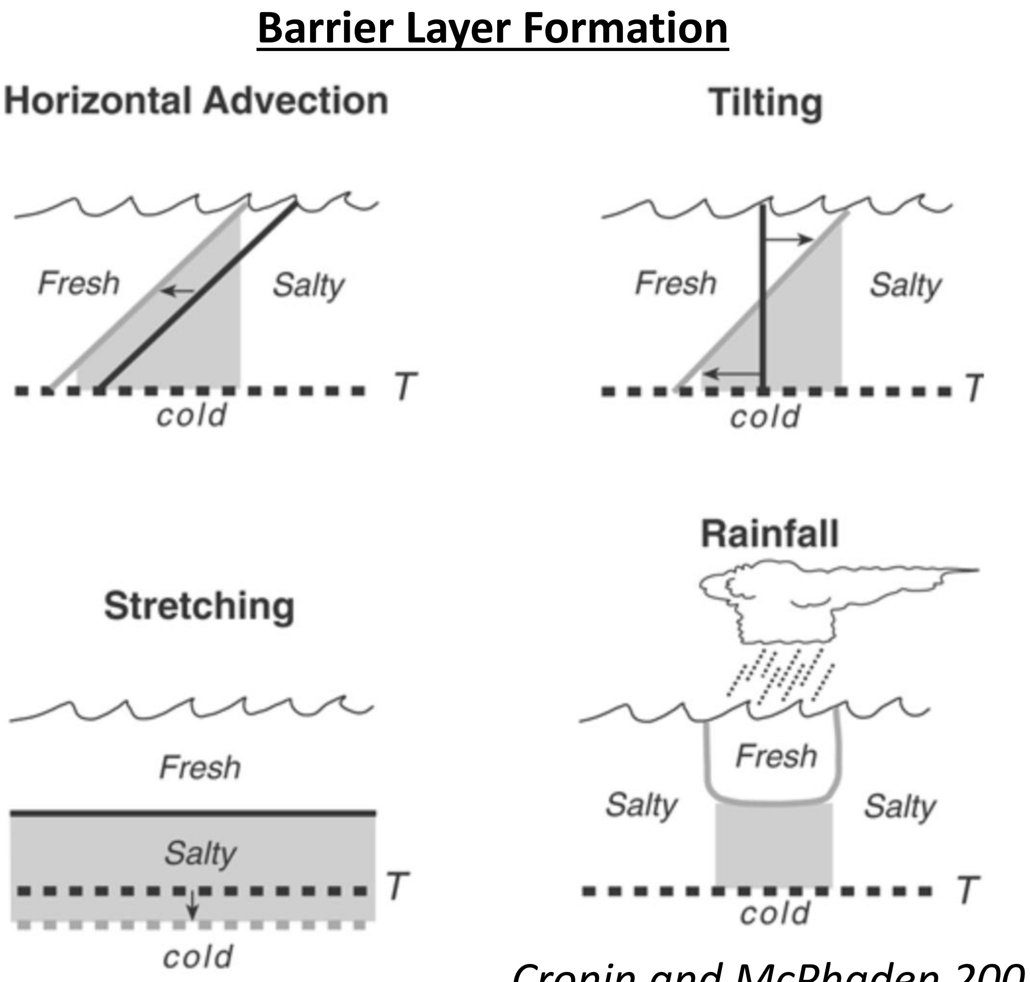
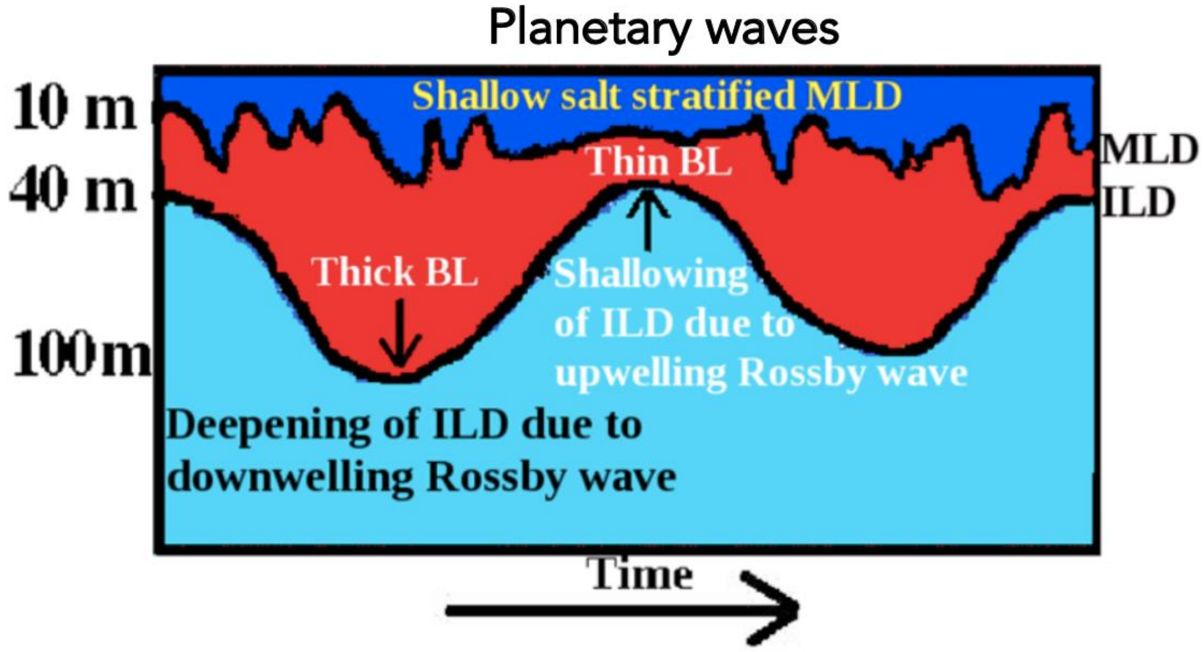


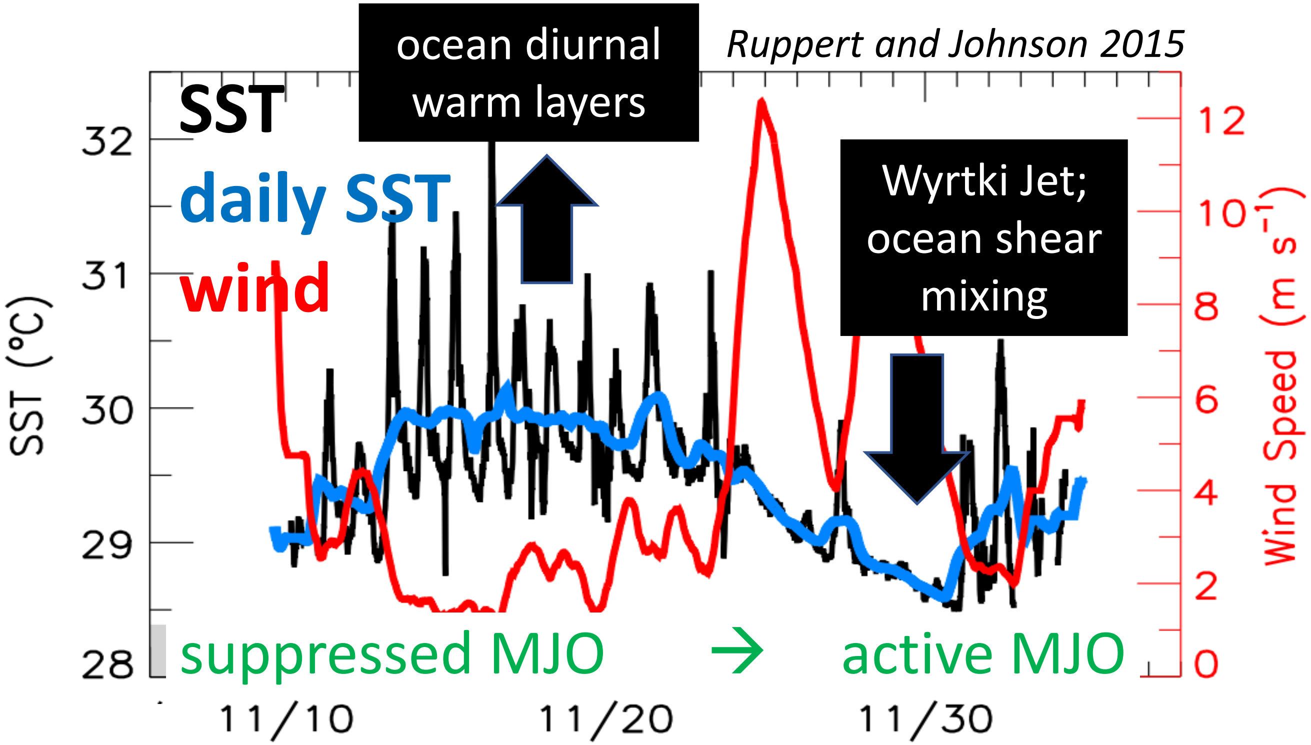
Cronin and McPhaden 2002

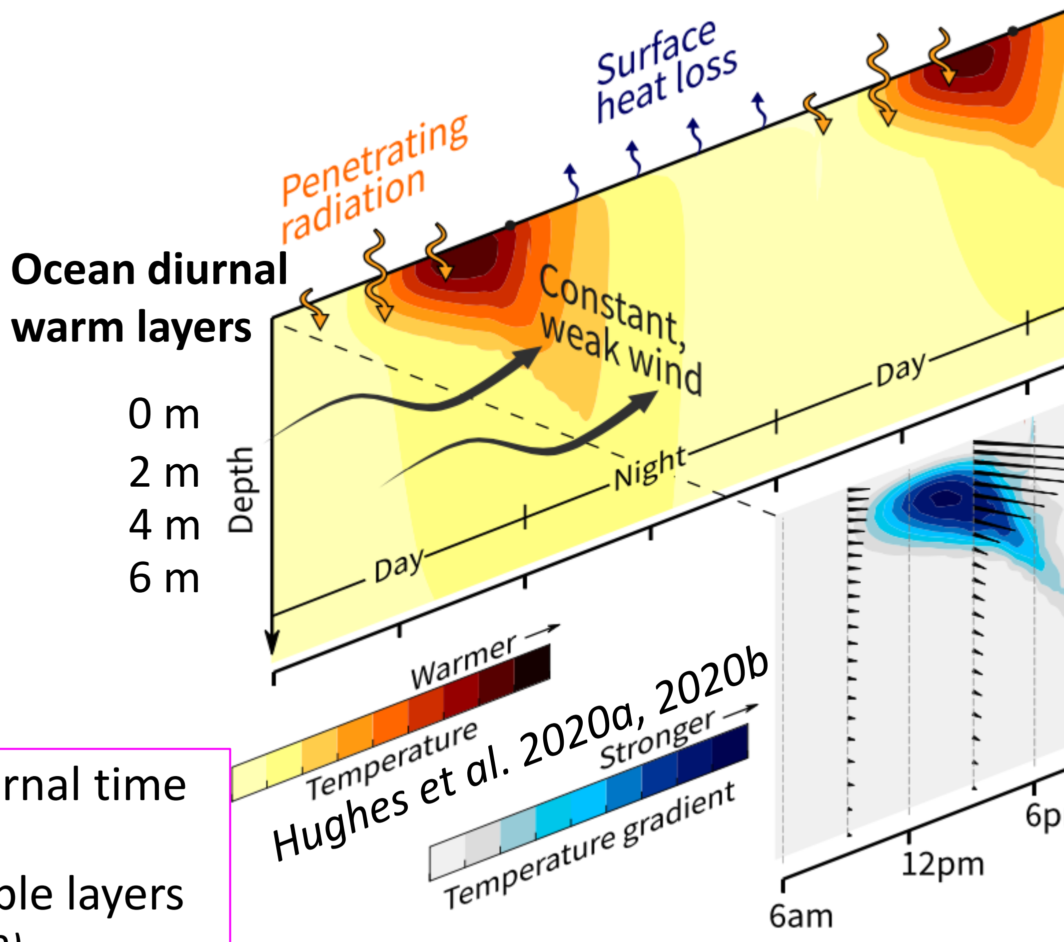


Girishkumar et al. 2011

1-3 hourly (subdiurnal) SST and flux coupling improves forecasts of ENSO, monsoons, and MJO

Masson et al. 2012, Terray et al. 2012, Seo et al. 2014



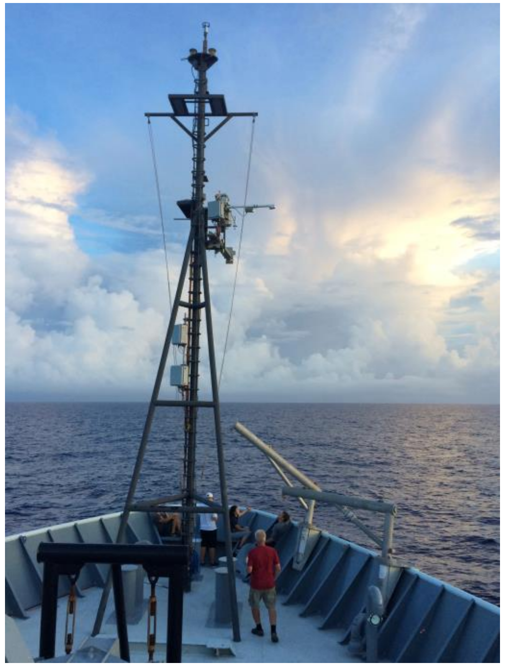


Surface stable layers amplify SST and air-sea flux variability on sub-diurnal time scales – diurnal warm layers, maybe also rain/fresh water layers
Opportunity: predictable except if strong advection or preexisting stable layers are present (*Fairall et al. 1996, Gentemann et al. 2008, Thompson et al. 2019)*

Evaporation describes how the ocean and marine boundary layer interact; measuring E is not trivial

Surface salinity as predictor of rain on seasonal+ scales:
Li et al. 2016a, 2016b, 2018, Hackert et al. 2020
https://www.SalientPredictions.com/
… excess S is directly related to *evaporation*

Salinity can also be used to track surface features long term (~conserved variable) *Hasson et al. 2019*

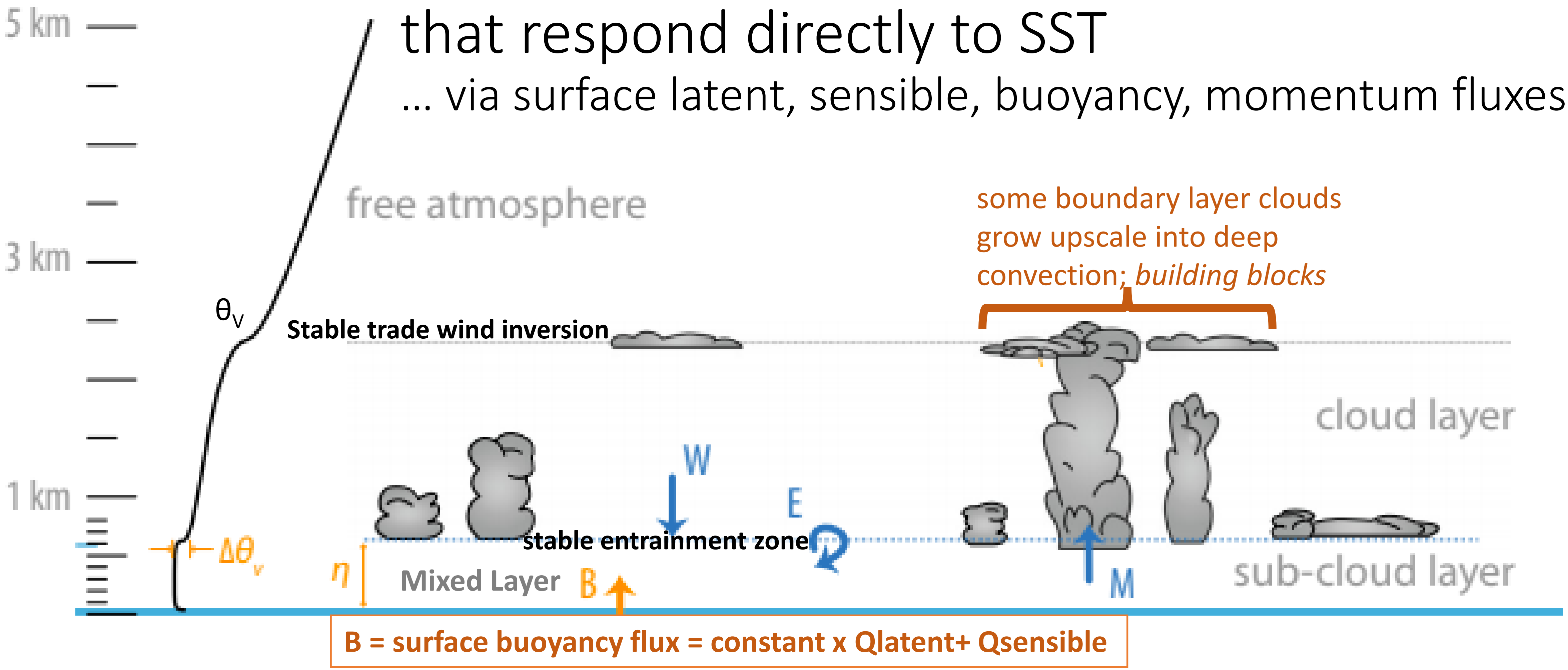


E is calculated by measuring *several variables* on ships, moorings, and autonomous ocean vehicles, or E is estimated using an algorithm like COARE with *several satellite retrievals* as input

<u>**Focusing on integrated moisture-related quantities can be useful for model diagnostics and empirical methods (LIM):**</u>
ocean salinity, P-E
trade winds in winter: ATOMIC
vertically integrated moisture
column saturation fraction
detrainment and entrainment
isotopes

Shallow boundary layer clouds are the ones that respond directly to SST

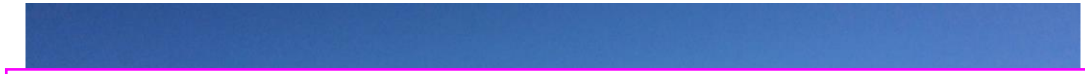
… via surface latent, sensible, buoyancy, momentum fluxes



- Mass flux at top of atmospheric boundary layer is proportional to surface buoyancy flux (*latent + sensible*)
- Surface fluxes are critical terms in column-integrated moisture and moist static energy budgets

Bony et al. 2017, Raymond 1995, Lilly 1968, Maloney 2009, Wolding and Maloney 2015b

Shallow boundary layer clouds move moisture, momentum, and heat between ocean and free troposphere

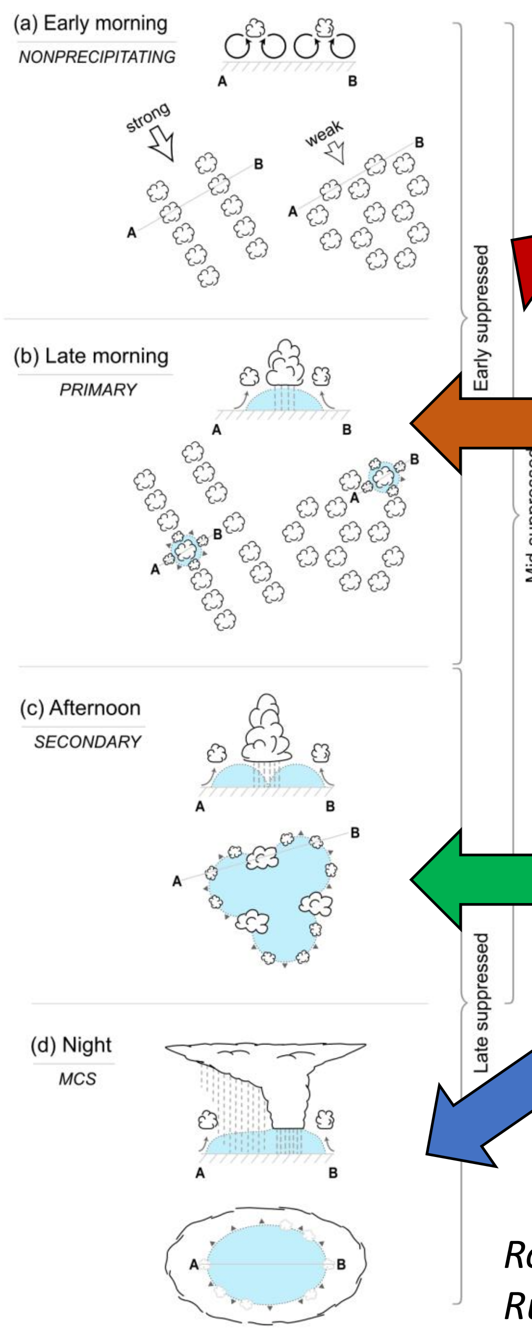


Not well-resolved from satellite; blocked in visible by upper level clouds; microwave and IR based satellite global precip products lacks precipitation features with diameter < 30 km or rain rate < several mm/hr

If we start paying attention when deep convection begins, the ocean-atmosphere part of the story is missed; we must observe, understand, parameterize, model the boundary layer

We do not observe SST and fluxes on the same time or space scales of convection

The ocean's impact on the deep atmospheric convection starts with non-precipitating boundary layer convection

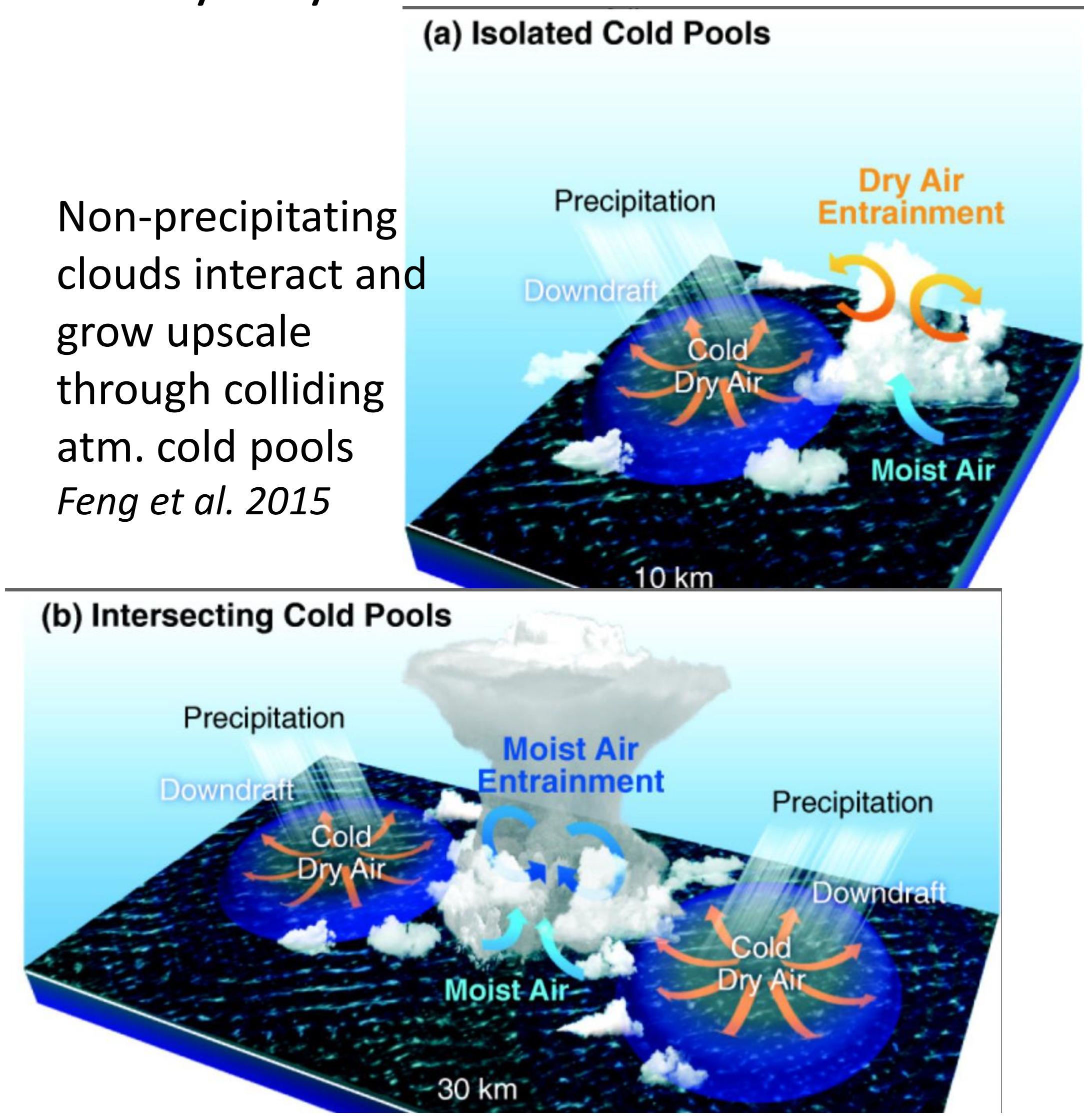


Small non-precipitating clouds are the ocean-forced precursors, or building blocks, to deeper clouds

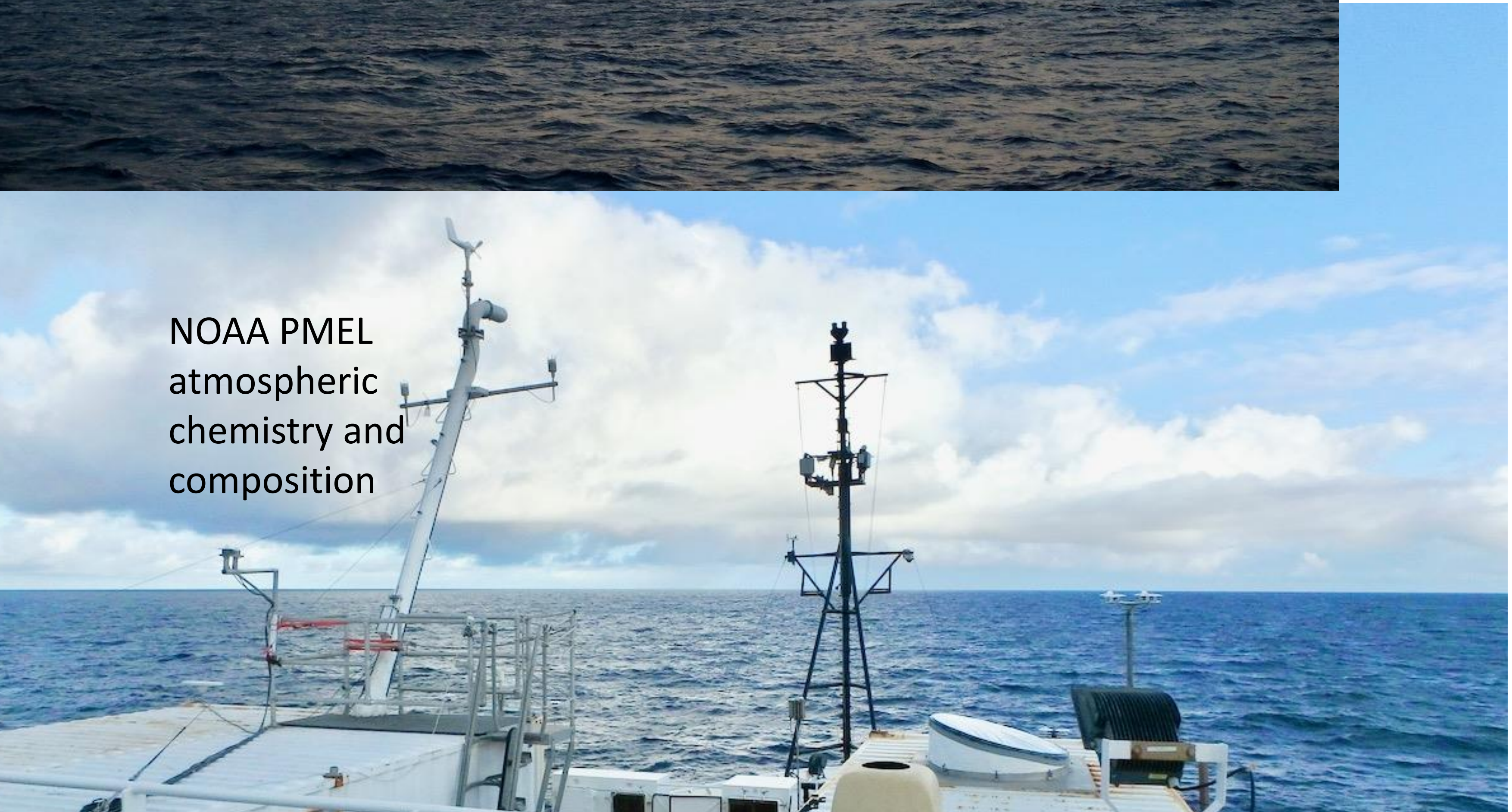
Precipitation systems *large* (> 30 km), *intense* (several mm/hr), and *persistent* enough (~30-60 min) are measured consistently from space

Rowe and Houze 2015
Ruppert and Johnson 2015, 2016

Non-precipitating clouds interact and grow upscale through colliding atm. cold pools
Feng et al. 2015



Open ocean conditions underneath African dust plumes. Caribbean. ATOMIC 2020. *Quinn et al. 2020*



NOAA PMEL atmospheric chemistry and composition

More work needs to be done on marine atmospheric chemistry in collaboration with cloud and boundary layer studies

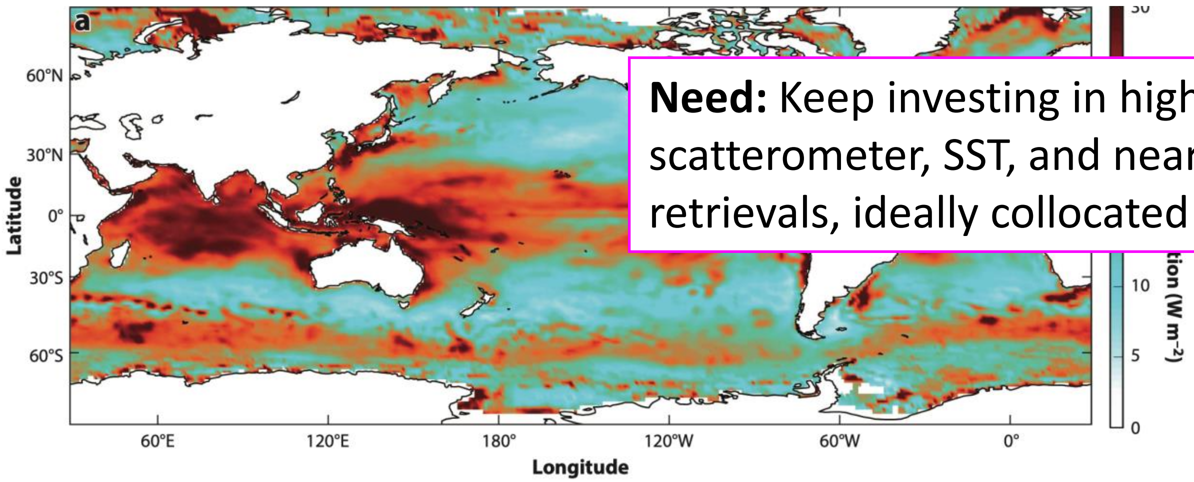
Benedetti et al. 2018 review paper: advances in aerosol predictions and data requirements

Reanalysis and satellite-based gridded products disagree:

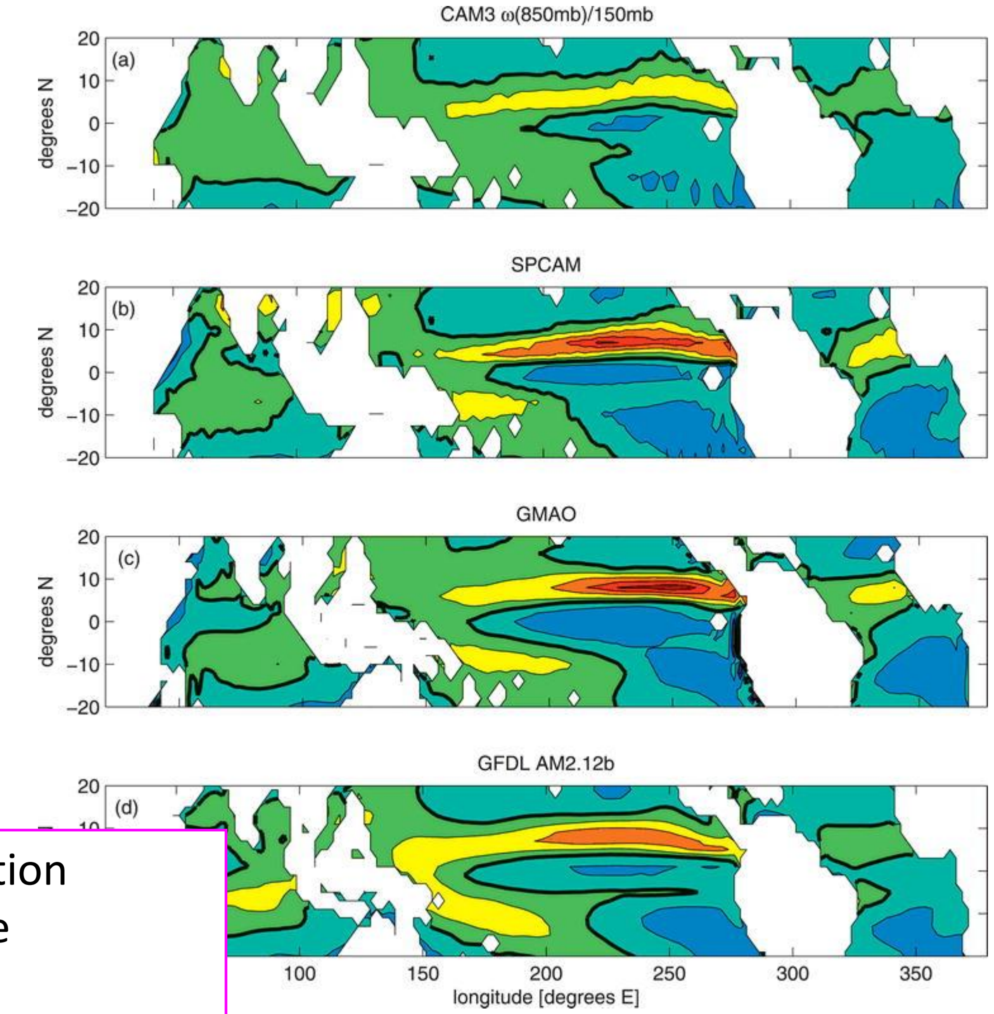
- fluxes
- low-level convergence response to SST
- tropospheric vertical profiles of T and humidity

Opportunity: Repeat model and reanalysis diagnostic exercises for different flavors of ENSO, MJO, BSISO, convective lifecycles

Std. Dev. Between 12 Q_{NET} products ~ 30 W m^{-2} *Yu 2019*



Need: Keep investing in high-resolution scatterometer, SST, and near-surface retrievals, ideally collocated



variations in modeled low-level convergence for a given SST pattern, *Back and Bretherton 2009*, recently adapted by *de Szoeke and Maloney 2020*

Reanalysis and satellite-based gridded products disagree:

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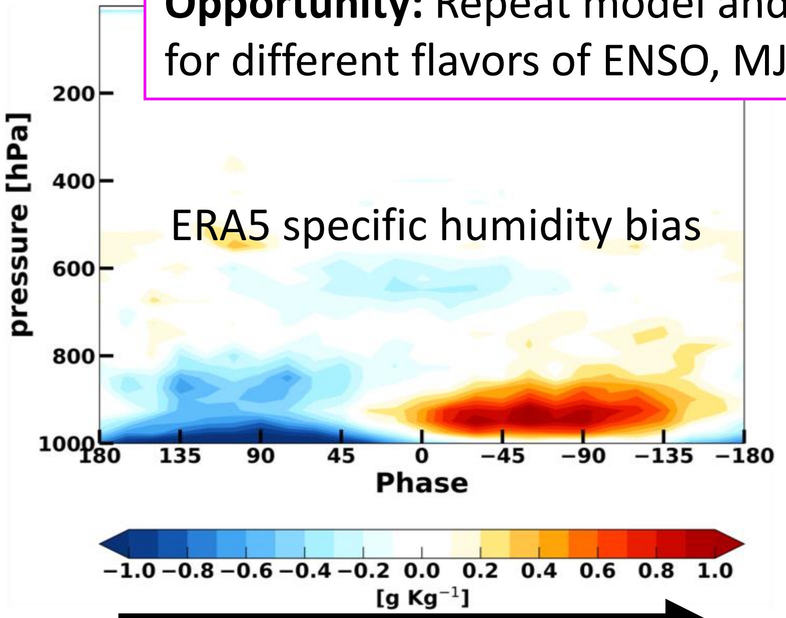
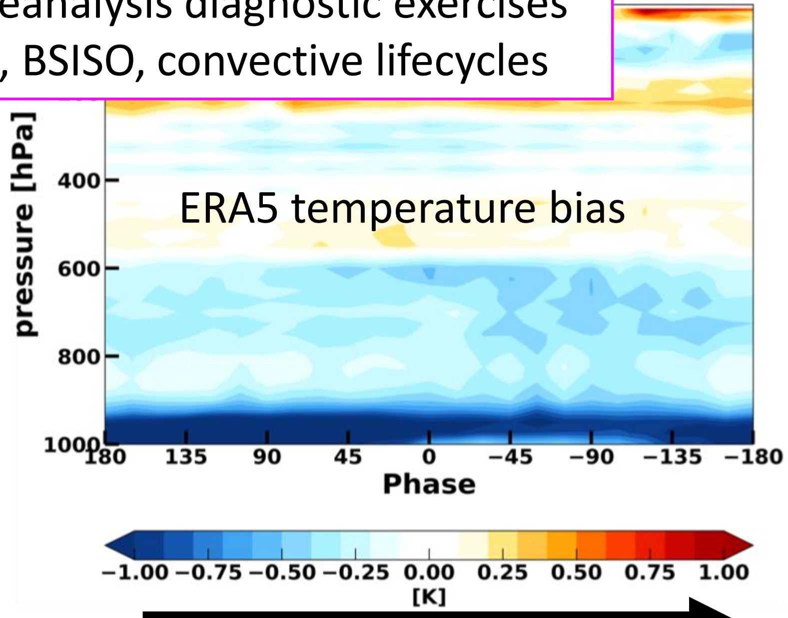


convective lifecycle



convective lifecycle

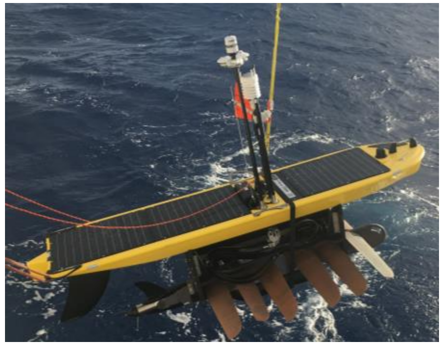
Considerable **disagreement amongst reanalyses** and between reanalyses and NOAA IGRA soundings, about how the **vertical structure of moisture and temperature evolve** in relation to convection

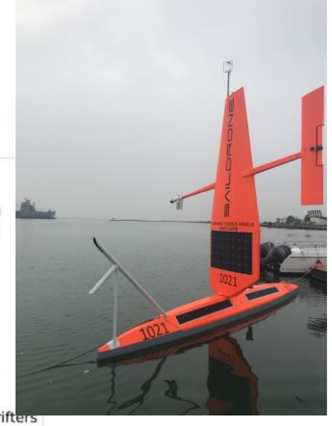
Fundamentally shapes how we understand relationship between convection and its thermodynamic environment

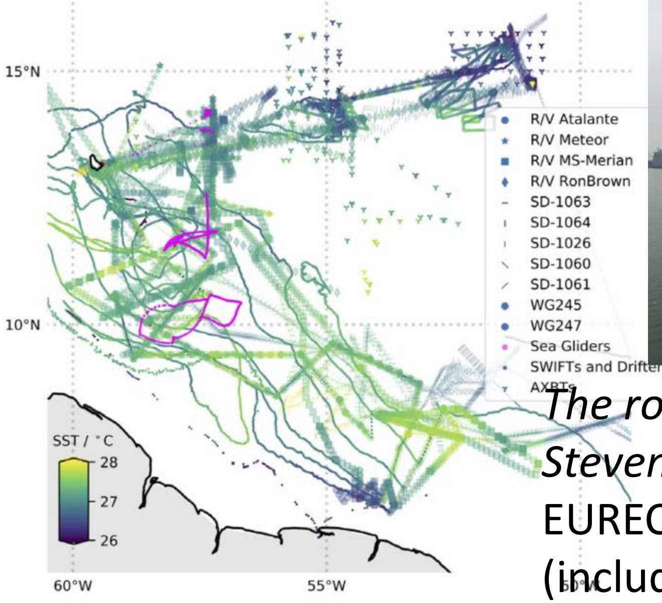
Additional efforts needed to **observe and constrain** vertical thermodynamic structure of tropics, particularly the **boundary layer**

c/o Brandon Wolding
Wolding et al. 2020a, 2020b

Room for improvements… to harness precipitation predictability from the ocean and air-sea fluxes





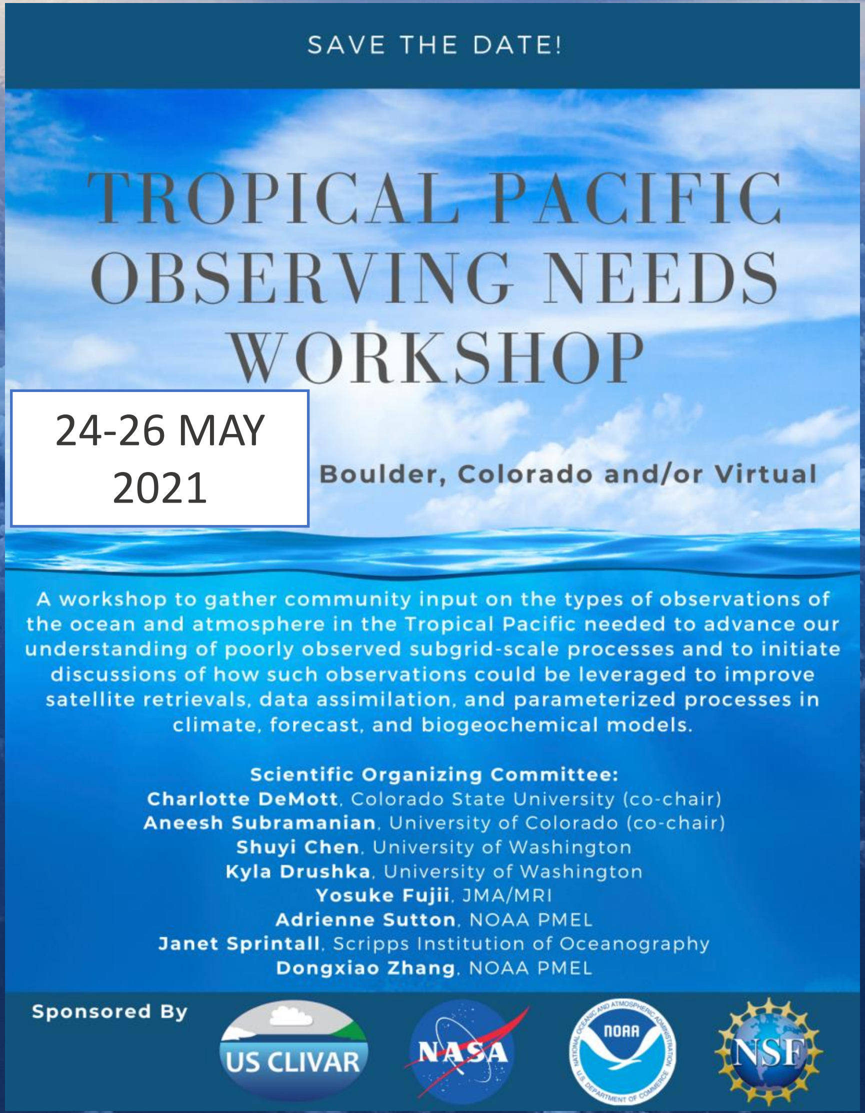


The robots are coming
Stevens et al 2020
EUREC4A
(includes ATOMIC)

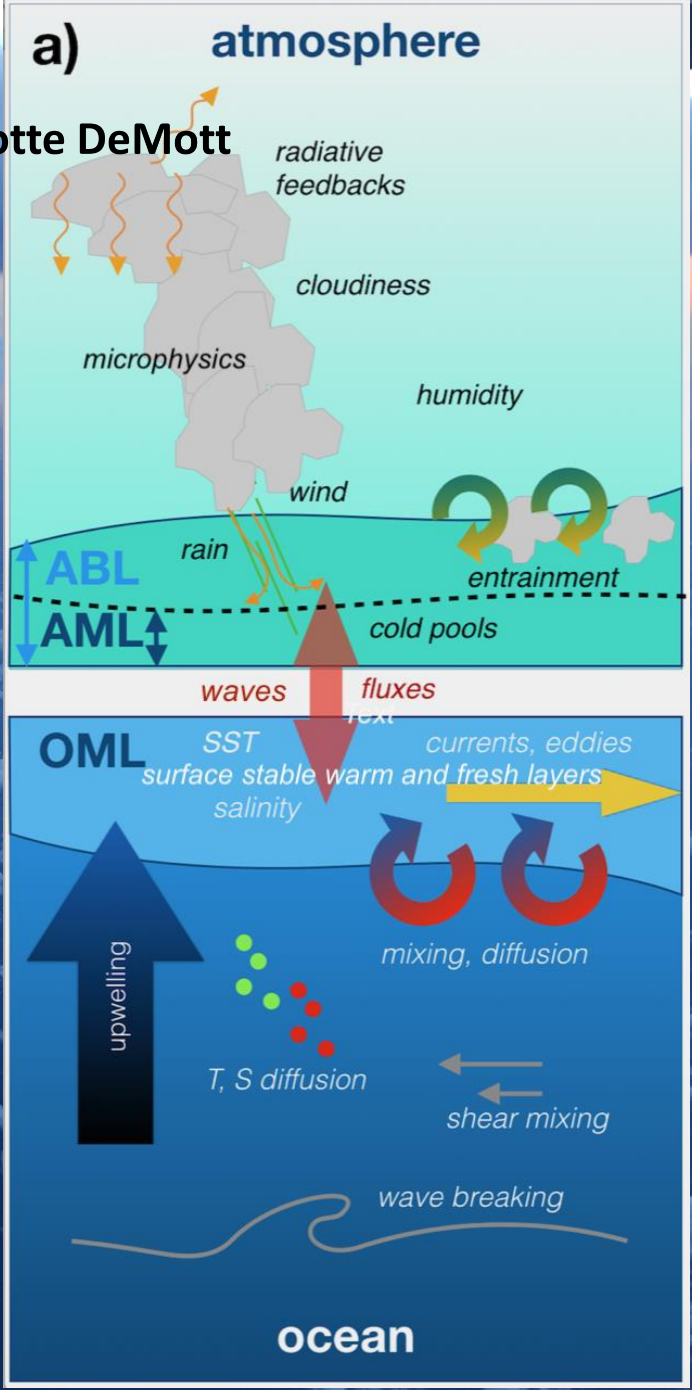
- **Improved coupled models** -> used for SST sensitivity studies; must deal with extratropical noise; **UFS medium and climate scale will share same coupled model physics in 2-5 yr**; must get fluxes and mean modeled ENSO state correct
- **Improved parameterizations** -> coupled, interactive, stochastic, **with realistic amount of noise, *Sardeshmukh et al. 2021***
- **Improved observations** -> distributed sampling, for budgets, super-sites with ocean+atmosphere profiles, satellite surface retrievals for flux calculations and vertical profiles, in-situ measurements to validate and improve satellite products and improve physical understanding used to advance models
- **measuring, modeling, evaluating each physical process**: ocean physics, SST, fluxes, boundary layer, shallow clouds, deep precipitation, teleconnections, ocean-moisture feedbacks
  - how well does coupled DA perform in each step?
  - how well are processes predicted with increasing lead time?
  - … in particular regimes in addition to mean total (convective lifecycle, enso diversity, mjo propagation clusters)
- **building databases** -> more examples with which to form empirical forecasts/analogs/LIMs
- **Better documentation, sharing, interaction between model and observation teams**

Sustained teamwork and creativity is needed for future progress:

1. **observations + modeling**
2. **atmospheric science + oceanography**
3. **interagency**
4. **international**



c/o Charlotte DeMott



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